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PRELIMINARY ASSESSMENT OF THE USE OF HEAT TRANSFER FLUIDS FOR SOLAR THERMAL ENERGY SYSTEMS

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This report contains a preliminary assessment, based on available data, of the extent to which various materials will be used as heat transfer media in solar energy systems and of mechanisms for their release to the environment. The emphasis is on solar thermal energy systems for industrial, agricultural and electrical production applications over the next 5-10 years. The study provides an assessment of consequences associated with transport and fate of the materials in the environment; identifies available pollution control techniques; and cites areas where further research may be required.

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FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory-Cincinnati (IERL-Ci) assists in assessing and developing new and improved methodologies that will meet these needs both efficiently and economically.

This study identifies the types and quantities of heat transfer fluids which may be used in the next decade in solar thermal energy systems. It also identifies routes for their release to the environmental and possible control techniques. The report provides background information for those concerned with the potential environmental impacts of solar energy development. It should also be useful in determining how significant a contribution this technology may make to environmental problems arising from the manufacture, use and disposal of heat transfer fluids. For additional information contact the Energy Pollution Control Division, IERL-Ci.

David G. Stephan
Director
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ABSTRACT

This report contains a preliminary assessment of the extent to which various materials will be used as heat transfer media in solar thermal energy systems and the routes for the release of these fluids to the environment. The emphasis is on solar thermal energy systems for industrial and agricultural applications and for electricity production over the next five to ten years. The study also identifies available pollution control techniques and cites areas where further research may be required.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

BTU	-- British Thermal Unit
CWA	-- Clean Water Act
DOE	-- U.S. Department of Energy
DOT	-- U.S. Department of Transportation
EPA	-- U.S. Environmental Protection Agency
FHSA	-- Federal Hazardous Substances Act
FMDF	-- fixed mirror distributed focus
IPH	-- industrial process heat
LCNT	-- low concentration nontracking
LFCR	-- line focus central receiver
LFDR-TC	-- line focus distributed receiver -- tracking collector
LFDR-TR	-- line focus distributed receiver -- tracking receiver
PFCR	-- point focus central receiver
PFDR	-- point focus distributed receiver
quad	-- 1×10^{15} BTU
RCRA	-- Resource Recovery and Conservation Act
STES	-- Solar Thermal Energy Program
TSCA	-- Toxic Substances Control Act

SYMBOLS

MW(e)	-- megawatts (electrical)
MW(t)	-- megawatts (thermal)

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SECTION 1

INTRODUCTION

The new venture of alternate forms of energy for commercial use raises the question of potential environmental impacts. The development of solar energy is one such venture and the pertinent questions apply to the use of heat transfer fluids in systems now under development or in demonstration stages. The use of high molecular weight hydrocarbons and silicone oils for heat transfer could result in significant insult to the environment if leaks or spills occurred that entered groundwater or surface water. In addition, if such materials are indicated for large-scale use, then detrimental enviromental effects may also result from their manufacture, transport, deployment, and disposal.

The present study was commissioned to investigate the rate at which solar thermal energy development would occur and to determine how this technology might affect the likelihood of releasing heat transfer fluids into the environment. To this end the study projects the volumes of heat transfer fluids that will be required during the next five to ten years for use in solar thermal energy systems, as well as the rates at which fluids may be released during manufacture, transport, use and disposal. The study also indicates what environmental regulations may constrain the use of these fluids, and the methods for disposing of them or of controlling their accidental release.*

This study reviews the state-of-the-art knowledge on the above topics, using data obtained from existing literature, from government agencies involved in solar energy development, and from industrial contacts.

The applications of primary concern in this study are medium-to-large-scale concentrating systems that yield process heat for industrial or agricultural use (Brown, 1980). Small-scale solar systems for residential or commercial use are not expected to use types or quantities of fluid that could have significant environmental impact.

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*Initially, another objective of this study was to assess the significance of the impacts which fluid release might have on the environment by determing the toxicity of the heat transfer fluids. However, it was found that the data available to address this question was incomplete. Because the effort required to perform an adequate literature seach and analysis of the toxicological properties of these compounds was beyond project resources, a discussion of the potential environmental problems arising from their release is not provided.

Of the components and materials that constitute current and proposed solar system designs, only heat transfer fluids are considered in this report. Other fluids necessary to some designs and applications -- such as heat engine working fluids and lubricating oils -- were deemed to be of less importance. Working fluids typically are used in relatively small quantities in plumbing and hardware, which are more precisely engineered, closed-loop subsystems; potential problems associated with manufacturing, disposal, or leaks are thus relatively small in magnitude. A similar argument holds for lubrication systems. Other factors involved in solar energy application, such as construction materials or materials related to end use, are beyond the scope of this study.

The study focuses on potential problems with designs that have undergone, or are approaching, demonstration and deployment. Emphasis is placed on systems that are expected to be fielded within the next five to ten years. More advanced concepts can receive full consideration of environmental effects as a part of long range planning cycles or in continuing studies similar to this one.

The remainder of the report has been divided into seven subsections: Conclusions, Recommendations, Industrial Solar System Designs and Processes, Heat Transfer Agents Used in Solar Systems, Fluid Release and Environmental Fate, Applicable Environmental Regulation and Pollution Control Techniques, and a Review of Federal R&D Activities Associated with the Manufacture and Disposal of Heat Transfer Fluids.

SECTION 2

FINDINGS AND CONCLUSIONS

RATE OF SOLAR THERMAL SYSTEM DEVELOPMENT

It is projected that the primary markets for solar thermal applications in the latter half of the 1980's will require approximately 6.5×10^{17} joules (0.62 quads) of energy in the United States. Of this, the greatest demand is expected for supplying electricity to displace peak-load gas and oil units, while some use is anticipated in Southern California for enhanced oil recovery. It is estimated that in the 1990's solar thermal applications will supply 1.2×10^{18} joules of electric power and 1.0×10^{18} joules of industrial process heat (IPH). Siting of these facilities will be predominately in the Southwest and Hawaii, although some plants might be installed in the South and Southeast.

During the 1980's and 1990's it is expected that water and water/glycol-based heat transfer fluids will be displaced by hydrocarbon and silicone oils as the chief heat transfer fluids. Some electric generating stations may use molten salts or liquid sodium.

The extent to which solar thermal energy development will place a strain on current production of heat transfer fluids is dependent upon the types of fluids used and upon how rapidly the energy technology is deployed. The projected demand of 1.0×10^{18} joules for IPH in the 1990's would require quantities of commercially available, non-aqueous heat transfer fluids (such as Dowtherm and Therminol) which are one or two orders of magnitude above present day production capacities for any one fluid. However, this quantity of heat transfer fluid is only a fraction of today's production rates for more common materials, such as the glycols. In either case, it is anticipated that the ten year lead time available to increase production before widespread deployment of solar systems should allow for orderly development of new manufacturing facilities to meet demand.

SOURCE OF SPILLS

Heat transfer fluids can enter the environment as a result of leaks and spills. In terms of volume, the annual spillage or leakage of heat transfer fluids in the 1980's will be small. For 1990, it is estimated that annual spillage rates on the order of 16,000 kg/year will occur from manufacture, transfer, use and storage operations. Thus, spillage of all heat transfer fluids used for solar systems in 1990 would be comparable to the annual spillage from an oil refinery which processes 100,000 barrels per day.

Most of this volume will be lost during fluid transfer and transport, situations for which containment of large spills may be difficult. Since most solar systems will be located in the Southwest while many heat transfer fluid producers are in the East, the spillage rate during transport may be above average. Spillage and leakage at a solar power site are expected to account for less than 20% of the volume of fluid lost during its life cycle. Most of this loss will be from storage facilities, where spills can be controlled with containment structures.

ENVIRONMENTAL FATE

Movement of solar heat transfer fluids through soils will be restricted by environmental and physical conditions. Many solar powered systems will be located in semi-arid regions, where little water moves on or through soils, or through aquifers. The viscosity of most heat transfer fluids for which data exists is high, restricting movement of heat transfer fluids in the soil.

It was found, however, that the information on the transport and fate of these pollutants is sparse; many of the newer fluids will have to be tested to determine their fate in the environment.

Heat transfer fluids tend to be high molecular weight, non-volatile compounds and mixtures. Air pollution thus is not generally a significant factor in evaluating potential environmental impact. The fluorocarbons are an exception to this rule. However, fluorocarbons have been considered only in a few designs of large-scale or high-temperature systems, and potential impacts are thus expected to be low.

SPILL PREVENTION AND CONTAINMENT

Use of standard methods of spill prevention and control during design, operation and maintenance of systems should adequately minimize large releases to the environment. Solar thermal energy facilities will employ safety measures against fluid release from transfer lines (e.g., double seals on pipe couplings) which are similar to those used in facilities of fluid manufacturers. Principal fluid releases at solar facilities are expected to come from storage vessels. These spills will be contained by earthern enclosures.

Some systems, such as those that utilize liquid metals (mercury or sodium), will require special considerations because of their relatively higher toxicity. However, there is little emphasis on use of these fluids at present, and no such systems are likely to approach large-scale deployment within the next several years. Prior to any such developments, stringent preventive and control measures will be necessary as an integral part of the design.

APPLICABLE REGULATIONS

Three acts -- the Resource Conservation and Recovery Act (RCRA), the

Toxic Substances Control Act (TSCA) and the Clean Water Act (CWA) -- could potentially impact decisions on heat transfer fluid use. Of these three, RCRA has potentially the most impact because it deals with the transport, storage and disposal of hazardous materials.

None of the fluids reviewed in this study were explicitly listed in RCRA under specific or non-specific sources, nor were they listed as hazardous substances. However, there is a paucity of toxicity data on many of these fluids and they may be listed in the future after more health-effects research is conducted.

Only one fluid, Dowtherm J, could be listed as hazardous because of its ignitability limits and, with the possible exception of several high temperature heat transfer salts, none would be expected to be classified as hazardous due to their corrositivity or reactivity.

SECTION 3

RECOMMENDATIONS

This study identifies a number of areas where incomplete knowledge exists of the factors influencing the impact of heat transfer fluids on the environment. The areas described below are considered to be the most important ones to address in further research on the use of these fluids in solar energy systems.

It is recommended that specific studies be instituted to explore toxic effects and migratory potential of those materials judged to be candidates for use as heat transfer fluids. In particular, toxicological investigations are needed on the actual fluids, not just of their major constituents. Migration effects should be evaluated by octanol-water partitioning and soil column leaching determinations for those materials for which such data are non-existent.

Since few of the solar system designs that have been proposed have reached the demonstration stage, periodic studies to reevaluate environmental impact potential need to be continued. This is particularly true since the environmental effects of currently proposed fluids vary widely, and since widespread deployment of any given systems may occur rapidly if the demonstration phase is successful. A continuing program to evaluate the potential for environmental insult should be planned to parallel the demonstration efforts, particularly for those plants projected to use the more toxic types of heat transfer fluids.

The evaluation of potential environmental impact is nearly always only a secondary objective of solar energy research and development programs and sponsoring agencies. Studies should be conducted that focus on this aspect of solar R&D. This would provide assurance that environmental effects are properly considered, while allowing the developer to focus attention on system development.

It is recommended that results of this and other environmental research on solar energy not be confined to presentation via media within the narrow solar energy field. Transfer of information to, and solicitation of involvement from, the areas of hazardous materials, waste disposal, and pollution control can have a positive influence on shaping sound, realistic regulatory and enforcement policies. In particular, many of the fluids being considered for solar systems are, or will be, used in other processes. Therefore, any cost/benefit analyses of the environment impacts and control of

these fluids in other industrial situations should also consider their use in solar systems.

Finally, a study is needed to determine the impact of pollution control and environmental monitoring requirements on design, siting, and operation of solar energy systems. This exercise would include cost-benefit analyses and an evaluation of impact on projected deployment schedules that result from applicable laws and regulations. Such an analysis may be critical to shaping environmental policy and to arrive at overall economic analyses for an industry which currently appears to have only marginal profit potential. It is noted, however, that such a study can probably not be adequately performed until additional data on fluid toxicity and transport and fate have been gathered.

SECTION 4

INDUSTRIAL SOLAR SYSTEM DESIGNS AND PROCESSES

This section describes the major systems proposed for solar thermal applications, the projected deployment of solar thermal technologies, and the environmental settings in which the deployment is likely to occur.

SYSTEM DESCRIPTIONS AND CONCEPTS

Solar thermal concepts can be characterized by the tracking capabilities of their collector/receiver systems. Two-axis tracking concepts, which are able to achieve the highest temperatures, include the Point Focus Central Receiver, the Point Focus Distributed Receiver (parabolic dish), and the Fixed Mirror Distributed Focus (hemispheric bowl). One-axis tracking concepts, capable of producing intermediate temperatures, include the Line Focus Central Receiver and two parabolic trough concepts: the Line Focus Distributed Receiver-Tracking Receiver and the Line Focus Distributed Receiver-Tracking Collector. The compound parabolic concentrator is a non-tracking concept.

Each of these concepts is described below. Included is a discussion of the working fluid(s) likely to be used for each concept and application.

Point Focus Central Receiver (PFCR) concepts employ large arrays of two-axis tracking mirrors to redirect the incident radiation onto a receiver located at the top of a fixed tower. The PFCR concept is illustrated in Figure 1. The working fluids associated with the central receiver concepts are localized in the tower area. The working fluid is pumped under pressure from the base of the tower through a riser to the receiver. After absorbing heat in the receiver, the fluid is transported through a downcomer to the base of the tower. Here, it is either circulated through a heat exchanger to provide steam for power generation or process heat or it is diverted to storage.

Both Rankine-cycle and Brayton-cycle heat engines have been proposed for use with the central receiver concepts. Near-term central receiver electric plants will probably use Rankine cycles. Rankine cycles operate in a temperature range of about 370° to 550°C (698° to 1022°F) (OTA, 1978). Water/steam will be used as the working fluid in the 10 MW(e) Barstow Pilot Plant. Because of the expense of heavy schedule pipe and fittings required to transport high pressure steam, it is more likely that a molten salt or metal working fluid will be used for commercial applications. These fluids will interface with a water/steam or organic Rankine cycle system through a heat exchanger.

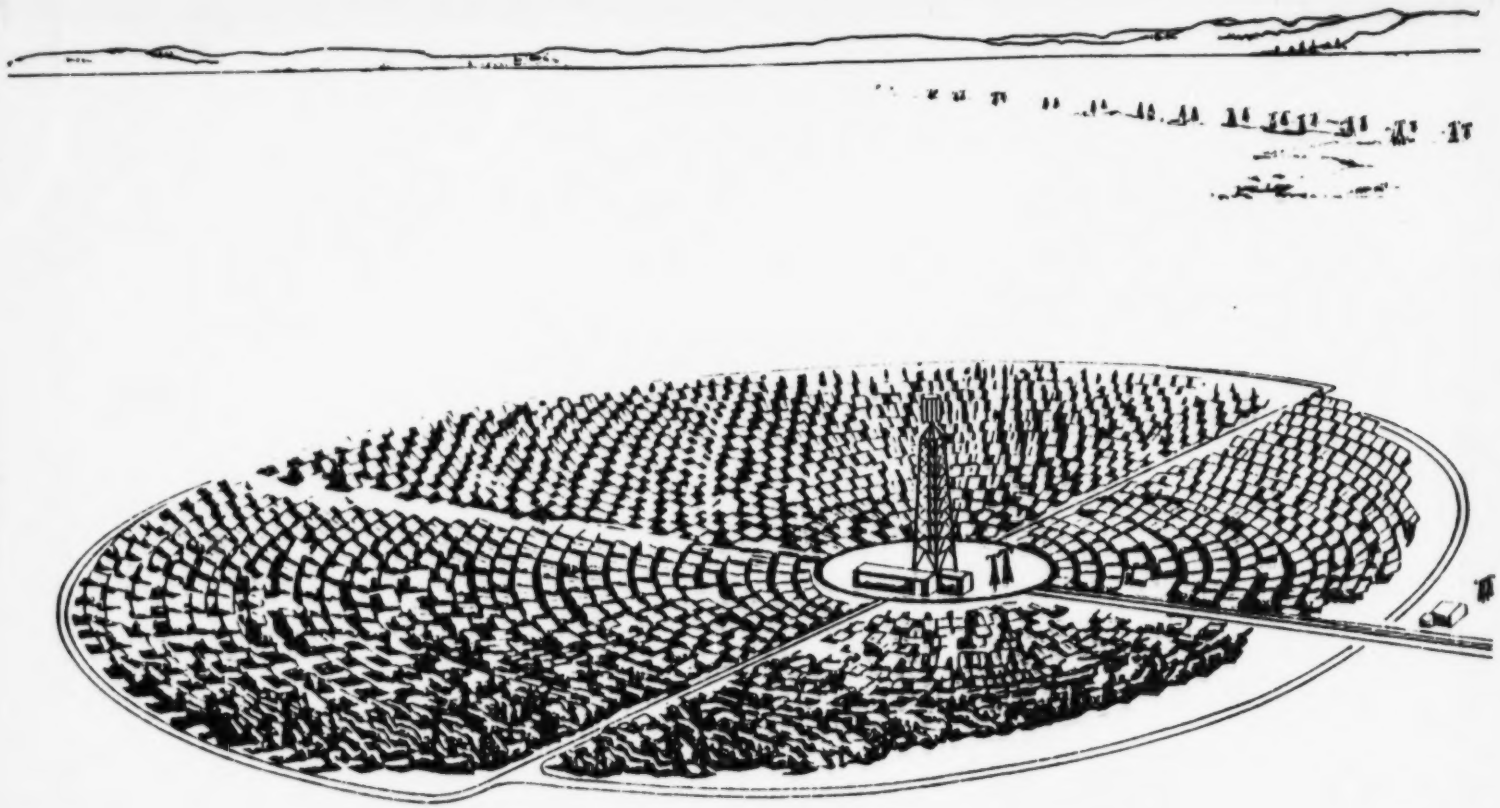

FIGURE 1. Point Focus Central Receiver (PFCR) Concept

An alternative to the Rankine cycle is the Brayton engine. Brayton-cycle engines operate typically at temperatures of about 815°C (OTA, 1978). The Brayton cycle operates on gas at all phases of its thermodynamic cycle. Near-term Brayton engines would use air as the receiver and engine working fluid; alternative concepts may use helium.

Solar central receiver technology can directly interface with a wide variety of industrial process heat (IPH) applications. Most of the proposed central receiver IPH concepts involve producing low-quality steam; however, by using different working fluids, higher quality steam can be produced as well as heated process air. Working fluids range from water/ethylene glycol mixtures at lower temperatures to organics at intermediate temperatures, to molten salts at high temperatures and air at the highest temperatures.

Point Focus Distributed Receiver (PFDR) concepts employ an array of two-axis tracking parabolic dishes that redirect incident radiation onto individual receivers located at the focal point of each separate parabolic concentrator. This concept is shown in Figure 2.

PFDR concepts can use Rankine, Brayton, or Stirling cycle engines to generate electricity. With both the Brayton and Stirling engines, the working fluid (helium or air) is localized at each dish. Rankine cycle concepts and process heat concepts require that the working fluid be piped from each dish to a central facility where it is used to generate electricity or to provide heat to a process plant or agricultural system. Thus, for these applications of the PFDR, the working fluid is not localized, but rather is transported throughout the entire plant area via extensive piping networks.

Near-term PFDR electric systems will employ a centralized Rankine cycle conversion system operating at about 400°C (752°F). The Shenandoah Demonstration Facility will use a silicone-base heat transfer fluid (Syltherm 800) (STES, 1980).

PFDR IPH systems will be able to operate up to a temperature of about 570°C (1050°F). Working fluids will include water/ethylene glycol mixtures at low temperatures, oils at intermediate temperatures, and molten salts at high temperatures.

The Fixed Mirror Distributed Focus (FMDF) concept consists of large, stationary hemispheric bowls, each with a boom-mounted receiver that can track the focal point in two axes. This concept is illustrated in Figure 3. The FMDF is capable of converting solar radiation to thermal energy at temperatures up to 650°C (1200°F) (STES, 1980).

The working fluid is piped from the collector field to a central facility where it is either circulated through a heat exchanger to produce steam for power generation or process heat, or it is diverted to storage.

FMDF test facilities presently use water/steam as a working fluid; however, because of the expensive, heavy schedule pipe and fittings required to transport steam at high temperatures and pressures, it is more likely

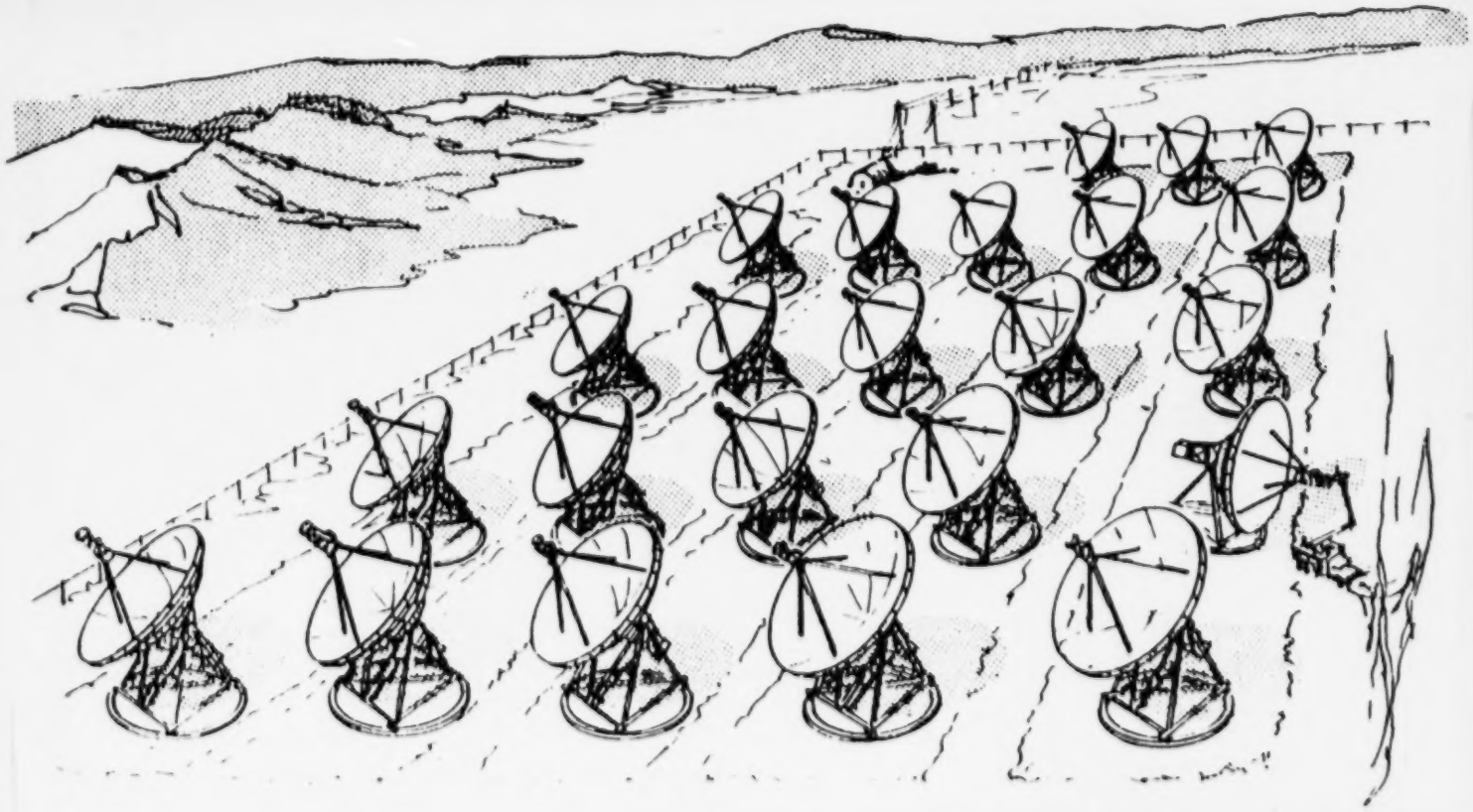

FIGURE 2. Point Focus Distributed Receiver (PFDR) Concept

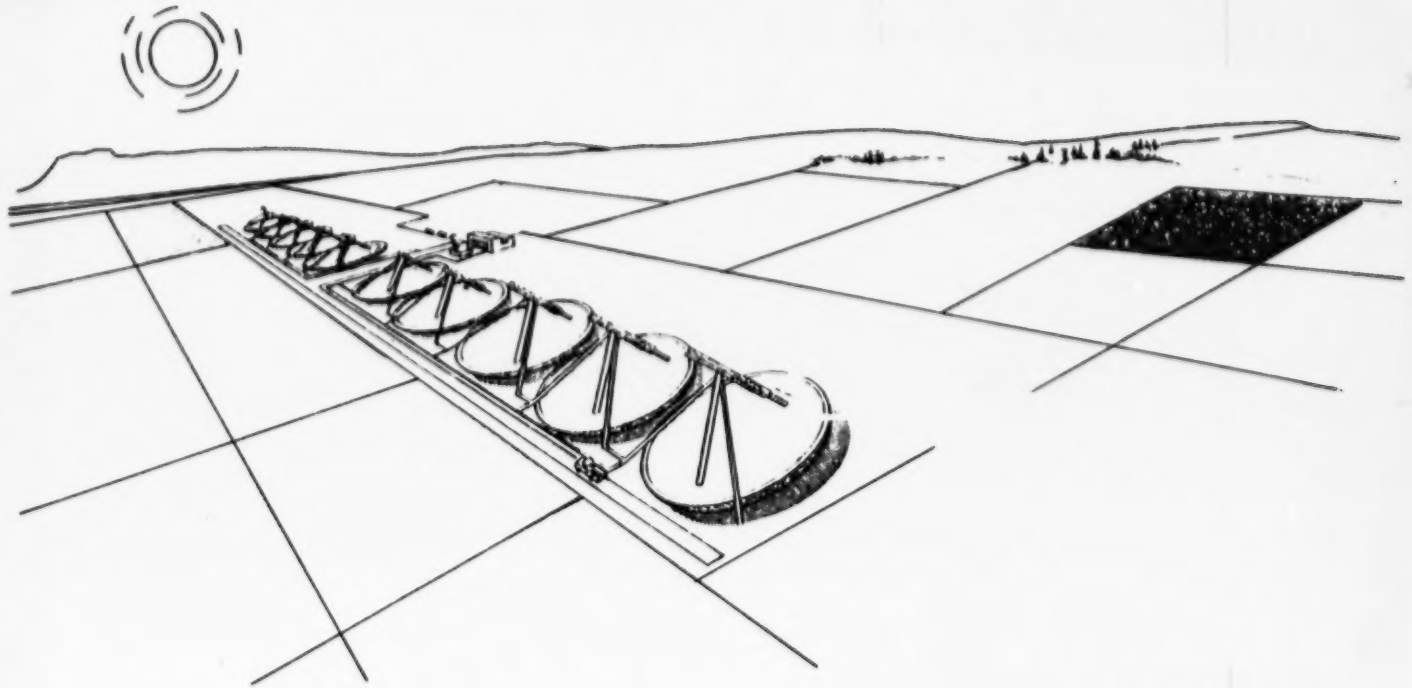

FIGURE 3. Fixed Mirror Distributed Focus (FMDF) Concept

that a molten salt working fluid will be used for commercialized electric applications. A wide range of working fluids is available for use with non-electric applications depending on the end-use temperature. Leading candidates include water-antifreeze solutions at low temperatures, oils at intermediate temperatures, and molten salts at higher temperatures.

The Line Focus Central Receiver (LFCR) has an array of one-axis tracking heliostats that focus incident radiation onto an elevated linear receiver. Figure 4 illustrates the LFCR concept. The LFCR can produce fluid temperatures up to 565°C.

The working fluid is piped from the central facility through the elevated linear receiver pipe where it absorbs heat. The fluid is then recirculated to the central facility to produce steam for power generation or to supply heat to the storage system.

Draw salt, a mixture of KNO_3 and $NaNO_3$, has been suggested as the working fluid for electricity production or high-temperature IPH applications (STES, 1980). Low-temperature IPH applications could use water, and intermediate-temperature applications could use heat transfer oils.

Other one-axis tracking concepts include the Line Focus Distributed Receiver-Tracking Receiver (LFDR-TR) and the Line Focus Distributed Receiver-Tracking Collector (LFDR-TC). The LFDR-TR field consists of an array of fixed-mirror parabolic troughs, each with a receiver that moves in a circular arc to track the focal line. The LFDR-TC consists of one-axis tracking mirror troughs that focus radiation onto a fixed linear receiver. The LFDR-TR and LFDR-TC concepts are shown in Figures 5 and 6, respectively. These parabolic trough concepts operate at temperatures from 100° to 400°C (212° to 752°F).

The working fluid is recirculated from a central facility through the receiver piping where it absorbs heat. Demonstration projects have used heat transfer oils as working fluids for both electric and IPH applications. Again, the expense of heavy schedule piping for steam transport will probably eliminate the use of water/steam as a working fluid for higher temperature applications.

The Low Concentration Nontracking (LCNT) concept consists of a series of stationary parabolic concentrators that redirect radiation onto a stationary receiver. This concept is illustrated in Figure 7. As with the other distributed systems, the working fluid circulates betwen the central facility and the collector field. Heat transfer oils, operating at temperatures of 230°C (450°F), appear to be the leading candidate for this concept.

PROJECTED DEPLOYMENT AND USE

This section briefly describes the market potential of solar thermal concepts currently proposed for electric and non-electric applications.

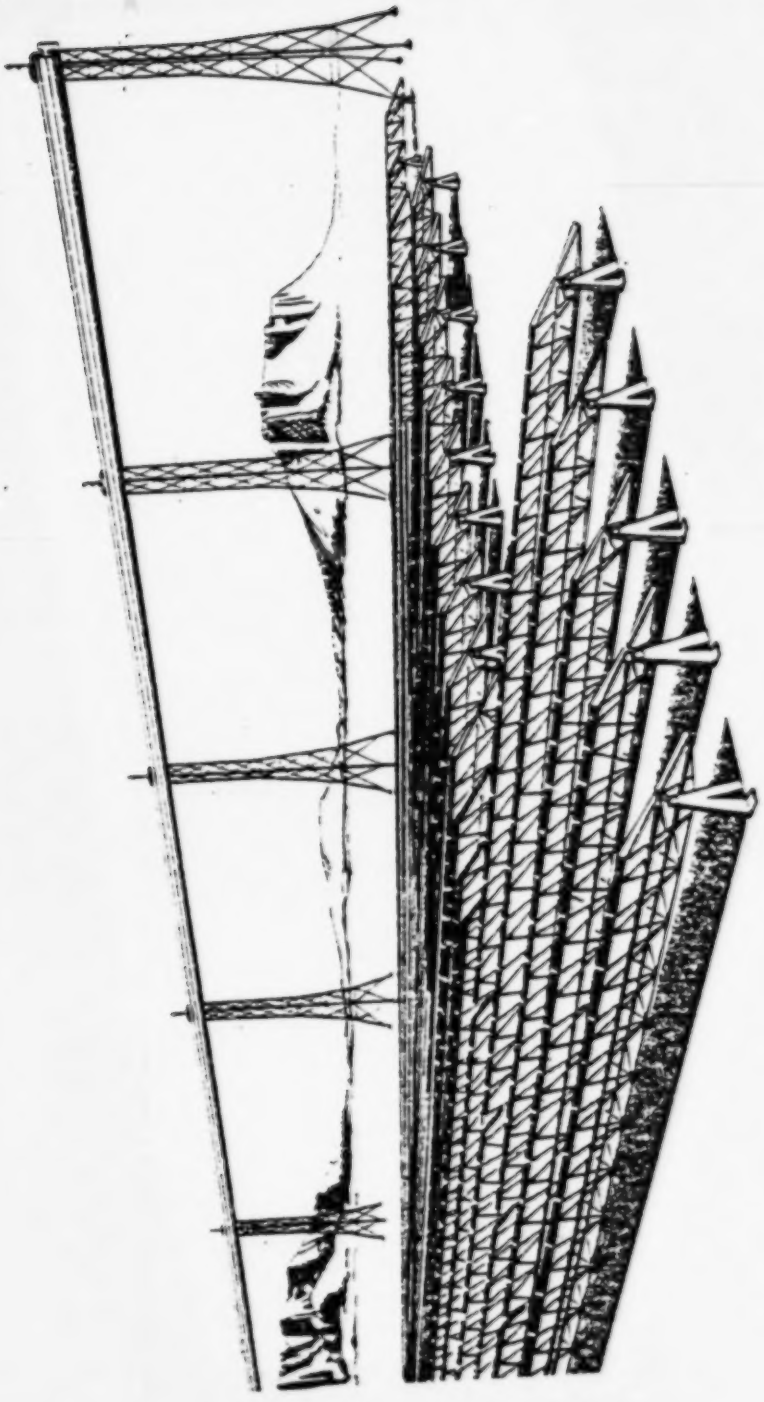

FIGURE 4. Line Focus Central Receiver (LFCR) Concept

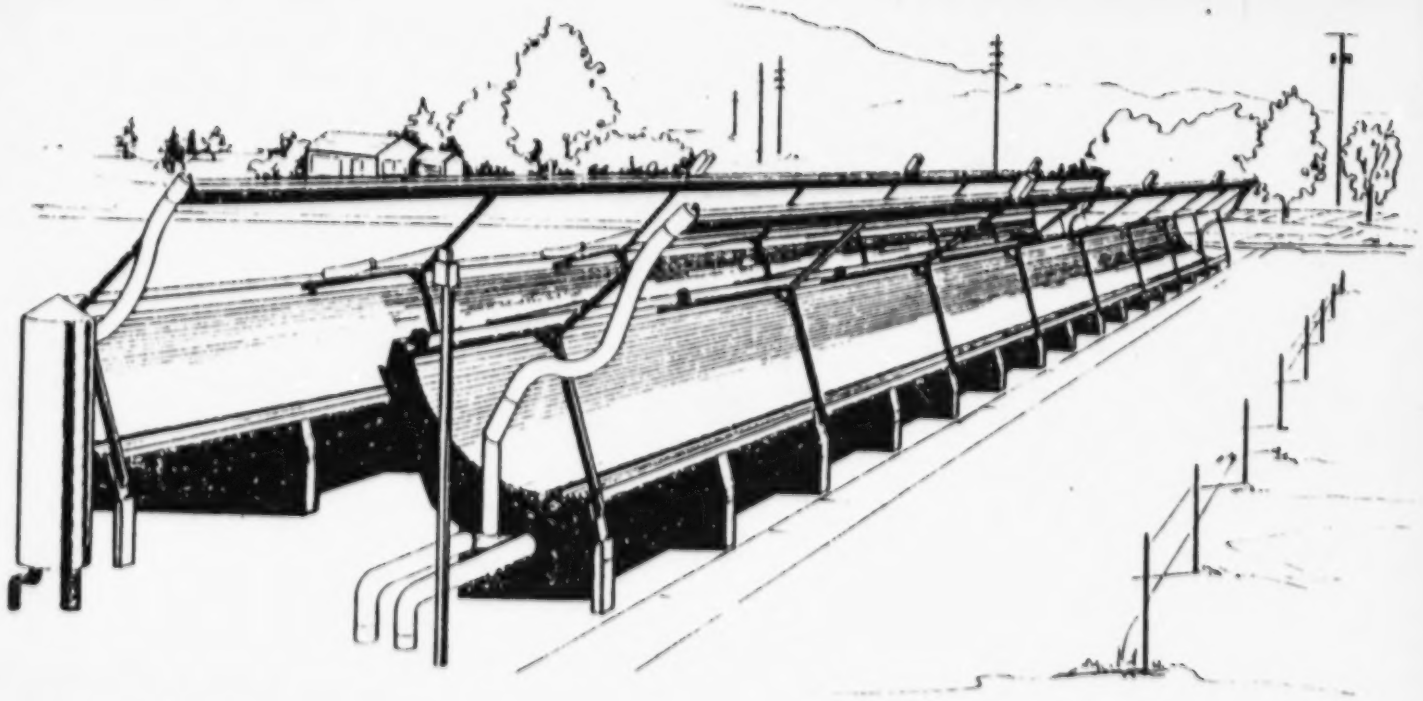

FIGURE 5. Line Focus Distributed Receiver, Tracking Receiver (LFDR-TR) (Segmented Trough) Concept

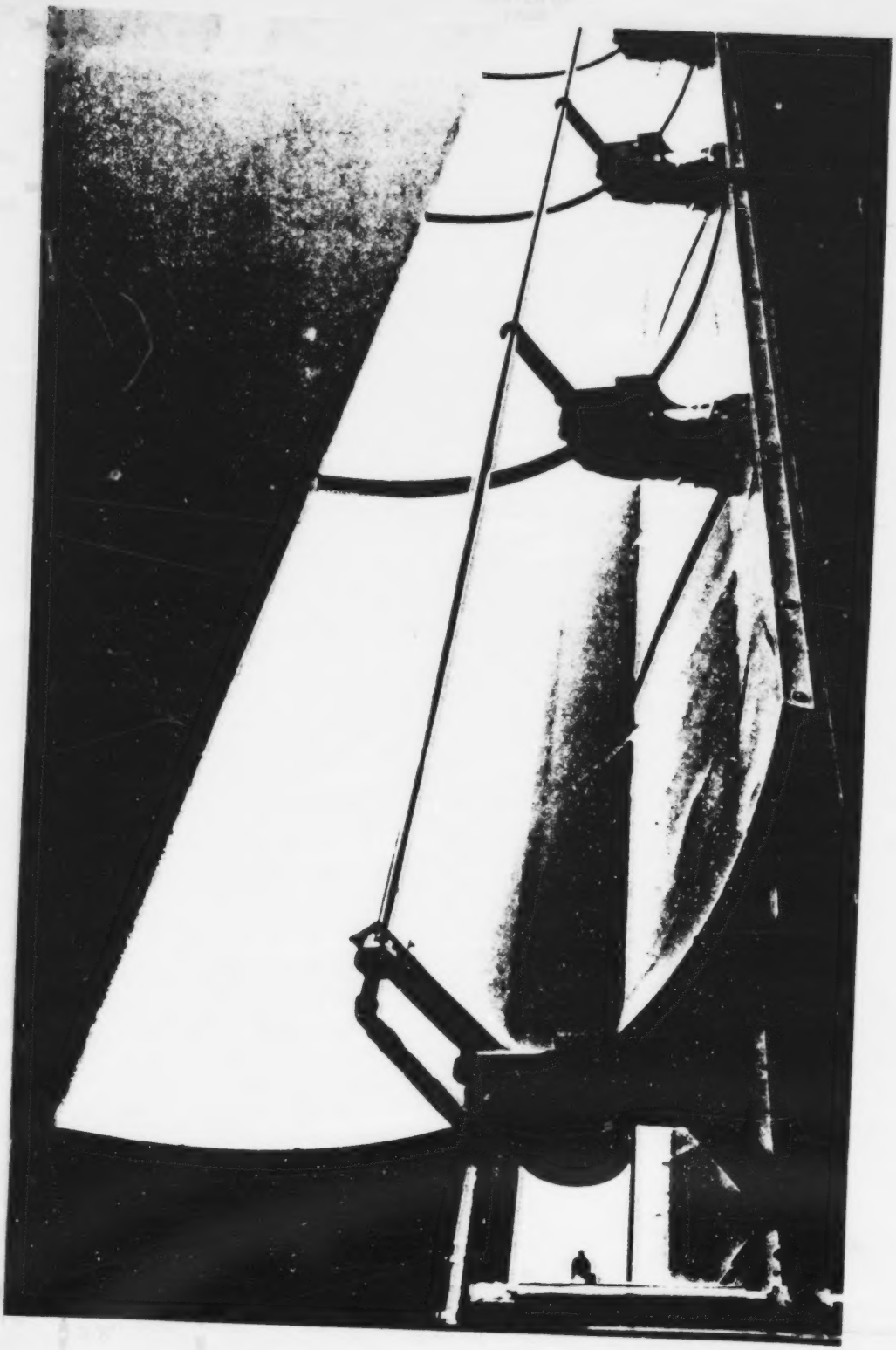

FIGURE 6. Line Focus Distributed Receiver, Tracking Collector (LFDR-TC) Concept

The draft Multi-Year Program Plan (STES, 1981) for the Solar Thermal Energy Systems (STES) program presents some recent estimates of potential market sizes for both electric generating and thermal applications. Although each of the major concentrating technology options could be applied to the generation of either electrical or thermal energy, the STES program focuses the majority of developmental effort into a specific application area. The areas of major focus are shown in the following table (STES, 1981).

TABLE 1. STES AREAS OF EMPHASIS FOR SOLAR THERMAL CONCEPTS

System	Application
Central receiver	Electric utility
Parabolic trough	Industrial process heat
Parabolic dish	Small community and on-site electric
Hemispherical bowl	Small utility electric

Parabolic trough systems are the closest to commercial development of all the solar thermal concepts.

The estimates of market potential presented in the STES program plan are discussed below for electric and non-electric applications. Although the STES program emphasizes an area of focus for each concept, these estimates are for the total market for all solar technologies.

Early market penetration (1985-1990) of solar thermal electric power is expected to occur mainly in areas of relatively high insolation, particularly California, Arizona, and New Mexico. In the mid-term (1990-2000), solar thermal electric plants will be competitive with gas and oil peaking plants in most locations and with intermediate-load plants primarily in California, New Mexico, Arizona, and Texas. It is surmised that solar thermal electric plants will compete for almost 1.2×10^{18} joules (1.14 quads) of the electric generating market in the 1990-2000 time frame. Beyond 2000, the market is expected to expand regionally.

Several conceptual designs for solar thermal electric plants have been proposed. Plant sizes from 0.5 to 300 MW(e) have been proposed for electric applications (STES, 1981). Initial market penetration of solar thermal electric plants is likely to be in the 10 MW(e) range.

The STES program plan suggests that a major portion of the near-term potential market for solar IHP will be for enhanced oil recovery in California. This application will be followed by some traditional IPH applications in areas of good insolation (eleven southwestern states) in the 1990-2000 time period. Beyond 2000, the solar IPH market will spread through all regions of the country.

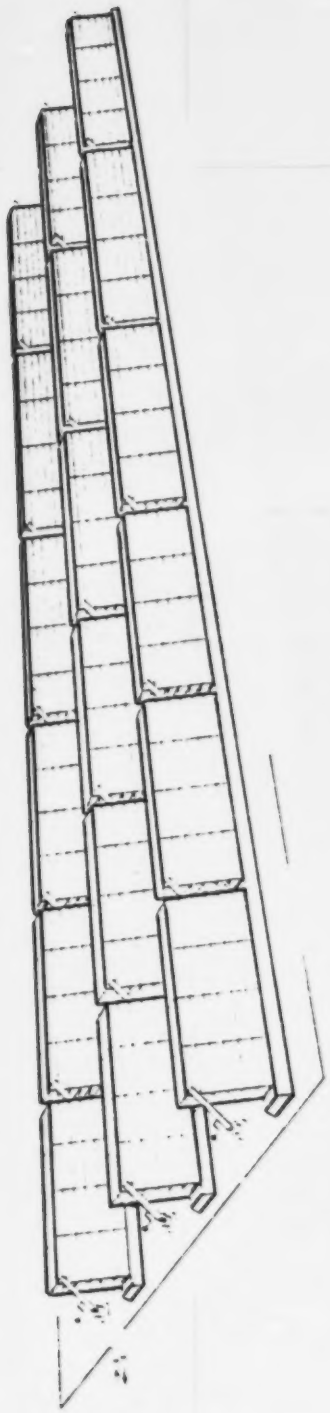

FIGURE 7. Low Concentration Non-Tracking (LCNT) Concept

Sandia National Laboratories (Skinrood, 1981) analyzed the distribution of industrial plants by average energy consumption MW(t) and end-use temperature. The following table summarizes the results of their findings:

TABLE 2. TYPICAL INDUSTRIAL PROCESS HEAT CONSUMPTION PER PLANT AT VARIOUS END-USE TEMPERATURES

End use temperature (^{o}C)	Typical plant consumption [MW(t)]
120	1- 10
120-230	1- 30
230-400	1- 100
400-650	1-1000

As described by Brown (1980), approximately half of manufacturing energy demand is in industrial process heat, and nearly half of that fraction is required at temperatures below 650^{o}C.

Significant potential for concentrating solar receivers exists in the IPH market at temperatures from 120^{o} to 650^{o}C. As shown in the preceeding table, solar thermal plant sizes could range from less than 1 MW(t) up to about 1000 MW(t) in this temperature range. Early entry into the market will probably occur with the smaller sizes. Several industries in which solar applications appear to be practicable have been identified: industrial inorganic chemicals, agricultural chemicals, sugar refining, hydraulic cement, enhanced oil recovery, and agricultural irrigation. The near-term market potential for enhanced oil recovery is thought to be 1.5 x 10^{17} joules (0.14 quads) and the mid-term market potential for IPH is estimated to be about 1 x 10^{18} joules (0.95 quads) (STES, 1981).

In summary, the total potential market for solar systems for electrical and non-electrical applications in the near-term (1985-1990) is about 6.5 x 10^{17} joules (0.62 quads), and in the mid-term (1990-2000) is about 2.2 x 10^{18} joules (2.09 quads). Market estimates are summarized in Table 3 (STES, 1981).

ENVIRONMENTAL SETTINGS OF CURRENT/PROPOSED SYSTEMS

Environmental factors influence decisions on the siting of solar IPH systems (Hooker et al., 1980). However, the emphasis has been on determining the effect of the environment on the siting process, rather than the converse. Favorable siting factors include high isolation levels; a non-polluted, low-humidity atmosphere to maximize earth-level insolation and to preclude collector surface deterioration; and the presence of strict air pollution regulations that mediate against traditional sources of energy, such as fossil fuel.

The influence of potential environmental releases on solar plant siting has not been considered in great detail. Fortuitously, most of the positive siting factors dictate locations where the results of releases may be of less immediate concern because of reduced exposure to the public and the environment.

TABLE 3. TOTAL POTENTIAL MARKET FOR SOLAR THERMAL APPLICATIONS

Period	Application	Location	Total size (energy displaced, exajoules)
1985-1990	Electric: displace peak-load gas and oil units	Southwestern states*	0.50
	Non-electric: enhanced oil recovery	California	0.15
		TOTAL	0.65
1990-2000	Electric: displace peak-load gas and oil units	All states	1.2
	Electric: displace intermediate-load gas and oil units	4 states**	
	Non-electric: IPH	Southwestern and some mid-western states	1.0
		TOTAL	2.2

* AZ, HW, CA, NV, CO, UT, KS, OK, TX, AR, NM
** CA, NM, AZ, TX

Land availability and land cost play an important role in determining areas of development for solar thermal plants. For IPH applications, sufficient land area must be available adjacent to the plant to minimize thermal energy transport losses and costs. In general, land costs are lower and land availability is greater in remote locations. For this reason, it is likely that remote solar thermal applications will be developed first.

In the United States, most of the current and proposed large-scale solar thermal systems are located in the southwest where large parcels of open, dry land are available.

Table 4 lists the locations of several solar thermal demonstration facilities under the STES program along with other solar application sites. With the exception of the PFDR IPH application in Shenandoah, Georgia, and the plants in Ontario, Oregon, and Fairfax, Alabama, all the plants are located in the southwest. Most are situated in relatively remote locations.

TABLE 4. SOLAR THERMAL DEMONSTRATION FACILITIES

Location	Concept	Application	Working fluid
Willard, NM	LFDR-TC	25-hp shallow well pumping--irrigation	Caloria HT-43
Coolidge, AZ	LFDR-TC	150-kW(e) Deep well pumping--irrigation	Oil
Crosbyton, TX	FMDF	5 MW(e) pilot plant	Water
Shenandoah, GA	PFDR	IPH-knitwear factory	Syltherm 800
Gila Bend, AZ	LFDR-TC	50-hp tail water pumping--irrigation	Unknown
Barstow, CA	PFCR	10 MW(e) pilot	Water
Ontario, OR	--	Potato cooking and processing	Water
San Antonio, TX	--	Process steam	Water
Fairfax, AL	--	Textile drying	Water

Much of the land in the southwest consists of desert basins and ranges that, on average, are much drier and have less vegetation than the remainder of the United States. The climate in this region is arid with annual precipitation averaging less than 50 cm (and in three-quarters of the area, less than 25 cm). Much of the area is arid because of the high evaporation rate. The effective moisture is less than the average precipitation would suggest, especially during the growing season. Probably 95% of the precipitation is lost by evaporation, transpiration, and seepage into the ground (Hunt, 1974). The extreme aridity leads to a scarcity of perennial streams and an abundance of playas. Supplies of surface water and ground water are sparse. In many of the basins, both surface and ground water are saline. In most parts of the region, the water table is deep and of doubtful quality.

Much of the area is dominated by a covering of sagebrush, creosote bush, or desert grass. Pinyon and juniper woodland are scattered throughout the region. The human population is concentrated in areas adjacent to water sources. Most of the rest of the area is open, unfenced desert.

The few solar plants which do not lie in the Southwest are generally found in the South and Southeast areas which still have relatively high levels of solar insolation. However, these areas also have relatively greater rainfall and vegetation or ground cover. Increased rainfall and ground cover may increase the environmental impacts of solar heat transfer fluid spills, depending on the quantities spilled.

SECTION 5

HEAT TRANSFER AGENTS USED IN SOLAR SYSTEM DESIGNS

GENERAL REQUIREMENTS FOR HEAT TRANSFER FLUIDS

In general, when selecting a heat transfer fluid, several factors must be considered. Typical properties include specific heat, thermal conductivity, density, and viscosity. Several recent reports by Parts et al., 1980; Searcy (Editor), 1978; OTA, 1978; Kahane, 1980; and Ullman et al., 1979b review fluid characteristics common to most heat transfer fluids. From an operational standpoint, parameters such as coefficient of thermal (volume) expansion, latent heat of vaporization, freezing point, useful liquid temperature range, chemical stability, and interaction with materials of containment play important roles in fluid selection. Finally, cost can often be the differential margin for selection of one fluid over another. Specific effects of each of these parameters on selection of a heat transfer fluid are stated in the above-mentioned references.

CATEGORIZATION OF HEAT TRANSFER FLUIDS BY RANGE OF TEMPERATURE APPLICATION

Selection of a proper heat transfer fluid begins with a determination of what temperature ranges are likely to be encournted during typical operating conditions. Fried (1973) provides a review of fluids appropriate for various operating temperatures. In the low temperature ranges (up to 177^{o}C), water of water-glycol mixtures are the most commonly used heat transfer fluids. Water of water-glycol fluids are preferred because of their low cost and abundance. For processes with operating temperatures rising above 177^{o}C (350^{o}F), fluids such as petroleum-based oils, silicone compounds, and synthesized organic fluids are used. Use of higher temperature fluids normally results in increasing costs. However, these costs are still quite reasonable, in the range of $0.25 to $0.75 per liter. For temperatures from 400 to 550^{o}C (750 to 1000^{o}F), inorganic salts are most commonly used. Again, the costs of these salts are higher per liter than those associated with lower temperature heat transfer fluids. For very high temperature applications, 550 to 1100^{o}C (1000 to 2000^{o}F), liquid metals are usually used as heat transfer media. However, the cost of using these materials is very high, and their use is generally restricted to cooling of nuclear reactors and extreme high-temperature reactions in the chemical industries.

Solar Heat Transfer Fluids

A variety of researchers -- Parts et al., 1980; Searcy (Editor), 1978; and Kahane, 1980 being the most recent -- have compiled lists of fluids which could be used as heat transfer media for solar installations. Additional sources for identification of heat transfer fluids include Chemical Engineering, 1981; Coastal Chemical Company Vendor Information; Hydroscience, 1979; Kreith et al., 1978; and DOE, 1978. The choice of which fluids to use depends mainly on the operating temperature range of a particular solar installation. Therefore, it is convenient to categorize the fluids according to the temperature ranges, although some overlapping of the fluids within these categories does exist. A list of fluids available using this classification criterion is presented in Table 5. As seen in Table 5, the majority of fluids available are in the low to moderate temperature ranges. This reflects the present temperature ranges used in most process applications at this time. High temperature heat transfer fluids are limited in number, expensive, and normally consist of liquid metals or mixtures of liquid metals. Based on available information, a brief description of each fluid's composition is presented in Table 5.

Usage of Heat Transfer Fluids in Solar Applications

References addressing solar heat transfer fluids over the last four years contain very little information about which types of heat transfer fluids are actually used. One of the more comprehensive sets of current heat transfer data comes from a report prepared by Parts et al., for the U.S. Department of Energy (1980). Information for that report was obtained through a survey questionnaire from 115 designers and manufacturers of solar collectors and collection systems. One of the questions asked in the survey was which heat transfer fluid the manufacturer recommended or was using. Table 6 summarizes their responses. Note that the results indicate frequency of response and not relative quantities of fluids used. The information provides a qualitative breakdown of fluids likely to be used in solar installations. On the basis of Table 6, it would appear low temperature fluids such as water, ethylene glycol, and propylene glycol solutions are more commonly used by flatplate collector manufacturers. The data are less conclusive for concentrating collector manufacturers. Another important point regarding data given in Table 6 is that each manufacturer is given equal weight in the table, although it can be assumed that the distribution of manufacturers, by level of production, is somewhat normal. Therefore, it is very difficult to project which fluids will be used based only on data from Table 6. Unfortunately, very little quantitative data on production for heat transfer fluids exist, mainly because of the proprietary nature of this type of information.

Not all fluids cited in Table 5 are in commercial production at this time. Monsanto's MCS fluids are considered to be in an experimental and/or development stage of production. Therefore, production of these compounds (MCS-1958, MCS-1980, and MCS-2046) is negligible. In addition, Dow Corning's X2-1162 silicone fluid is still considered to be a developmental fluid. However, the remainder of the fluids are available at commercial production levels according to the Parts et al., survey. For the next few years water

TABLE 5. HEAT TRANSFER FLUIDS AVAILABLE FOR USE IN SOLAR APPLICATIONS

Fluid	Manufacturer	Composition
A) Low Temperature Fluids (-107 to 177°C)		
Water	--	Water with some rust inhibitors
Ethylene Glycol-Based Fluids		
Dowtherm SR-1 (50 wt %)	Dow Chemical Company	Ethylene glycol with inhibitors
Prestone II (50 vol %)	Union Carbide Corporation	Ethylene glycol with inhibitors
Sunsafe 100 (33 vol %)	Nuclear Technology Corporation/ NPD Energy Systems, Inc.	Ethylene glycol with inhibitors
Sunsafe 130 (50 vol %)		Ethylene glycol with inhibitors
UCAR TR-17 (50 vol %)	Union Carbide Corporation	Ethylene glycol with inhibitors
Zerex	PPG Industries, Inc.	Ethylene glycol with inhibitors
Propylene Glycol-Based Fluids		
Dowfrost (50 wt %)	Dow Chemical Company	Propylene glycol with inhibitors
Practical Solar Fluid	Practical Solar Heat, Inc.	Propylene glycol with inhibitors
Sunsafe 200 (33 vol %)	Nuclear Technology Corporation/ NPD Energy Systems, Inc.	Propylene glycol with inhibitors
Sunsafe 230 (50 vol %)		Propylene glycol with inhibitors
Sunsol 60	Sunworks	Propylene glycol with inhibitors
UCAR FF-35 (50 vol %)	Union Carbide Corporation	Propylene glycol with inhibitors
Freons		
Freon 11	E. I. du Pont de Nemours and Company	Trichloromonofluoromethane
Freon 114	E. I. du Pont de Nemours and Company	Dichlorotetrafluoroethane
Freon TA	E. I. du Pont de Nemours and Company	Trichlorotrifluoroethane (89 wt %), acetone (11 wt %)
Petroleum Based Alphatic Hydrocarbons		
Diala AZ	Shell Oil Company	Refined mineral oil with oxidation inhibitors
Synthetic Alphatic Hydrocarbons		
Brayco 888	Bray Oil Company	Synthetic aliphatic hydrocarbons
Esters		
Therminol 44	Monsanto	Modified ester based fluid
Silicones		
Syltherm 444	Dow Corning Corporation	Poly (dimethylsiloxane)

(Continued)

TABLE 5. (Continued)

Fluid	Manufacturer	Composition
B) Medium Temperature Fluids (-40 to 316°C)		
Petroleum-Based Aliphatic Hydrocarbons		
Caloria HT-43	Exxon Corporation	Mixture of petroleum hydrocarbons and selected additives
Mobiltherm 603	Mobil Oil Company	Mixture of paraffinic-base hydrocarbons
Silogram Heat Transfer Fluid 43	A. Margolis and Sons Corporation	Paraffinic-type oil with oxidation inhibitor
Sunoco Heat Transfer Oil 21	Sun Oil	Paraffinic-type petroleum oil
Sunoco Heat Transfer Oil 25	Sun Oil	Paraffinic-type petroleum oil
Thermia Oil C	Shell	Refined mineral oil with oxidation inhibitor
Dowtherm HP	Dow Chemical Company	Unknown -- proprietary
Suntemp 1	Resource Technology Corporation	Unknown
Texatherm	Texaco, Inc.	Unknown
Synthetic Aliphatic Hydrocarbons		
ESH-4	Ethyl Corporation	Hydrogenated polyalphaolefin
ESH-5	Ethyl Corporation	Hydrogenated polyalphaolefin
ESH-6	Ethyl Corporation	Hydrogenated polyalphaolefin
H-30	Mark Enterprises, Inc.	Synthetic, polymeric hydrocarbon
Uniroyal PAO-13C	Uniroyal, Inc.	Synthetic, saturated polyalphaolefin
Aromatic Hydrocarbons		
Dowtherm J	Dow Chemical Company	Alkylated aromatic hydrocarbons
Dowtherm LF	Dow Chemical Company	Mixture of diphenyloxide and methylated biphenyl
Mobiltherm 600	Mobil Oil Company	Mixture of aromatic and paraffinic hydrocarbons
MCS-1958	Monsanto	Halogenated aromatic compounds
MCS-1980	Monsanto	Mixed terphenyls and higher polyphenyls
MCS-2046	Monsanto	Modified mixed terphenyls and higher polyphenyls
Therminol 55	Monsanto	Mixture of synthetic hydrocarbons
Therminol 66	Monsanto	Modified terphenyls
Therminol 88	Monsanto	Mixed terphenyls
Mobiltherm 605	Mobil Oil Company	Unknown
Esters		
Stauffer 3664-A	Stauffer Chemical Company	Polyol ester-based fluid

(Continued)

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TABLE 5. (Continued)

Fluid	Manufacturer	Composition
Ethers		
Dowtherm A	Dow Chemical Company	Eutectic mixture of diphenyloxide and biphenyl
Dowtherm G	Dow Chemical Company	Mixture of diaryl and triaryl ethers
Therminol VP-1	Monsanto	Eutectic mixture: diphenyl oxide (73.5 wt %), biphenyl (26.5 wt %)
UCON HTF-500	Union Carbide Corporation	Polyalkylene oxide ether
Silicones		
SF-96 (20)	General Electric	Poly (dimethylsiloxane)
X2-1162	Dow Corning Corporation	Poly (dimethylsiloxane)
Syltherm 800	Dow Corning Corproation	Unknown
C) Moderate to High Temperature Fluids (149 to 539°C)		
HITEC	Coastal Chemical Company	Salt mixture
D) High Temperature Fluids (49 to 760°C)		
Mercury		Mercury
Sodium		Sodium
Potassium		Potassium
NaK		Mixture of sodium and potassium

and aqueous solutions of ethylene glycol and propylene glycol will continue to dominate the market for heat transfer fluids. However, as high-temperature solar plants come on-line, aqueous solutions will be replaced by higher temperature fluids such as those listed in Table 5, increasing the demand for these types of products.

TABLE 6. MANUFACTURER'S RECOMMENDATIONS OF HEAT TRANSFER FLUIDS

Fluid type	Percentage of responses: Flatplate collector manufacturers	Concentrating collector manufacturers
Petroleum-based aliphatic hydrocarbons	2.3	15.8
Synthetic aliphatic hydrocarbons	2.3	*
Aromatic hydrocarbons	1.6	18.4
Ethylene glycol/water	18.6	15.8
Propylene glycol/water	17.0	5.3
Water	29.5	13.1
Ethers	0.8	5.3
Esters	0.8	*
Silicones	8.5	15.8
Fluorocarbons	0.8	2.6
Other	17.8	7.9
	100.0	100.0

*Unknown

Recycle of Heat Transfer Fluids

According to industrial sources, very little recycling of hydrocarbon heat transfer products is expected. At the present time, the cost of recycling makes its application prohibitive. When the solar industry produces enough spent fluids to support a recycling industry economically, then the fluids will be recycled. Questions pertaining to how large an industry is needed and when this will occur are beyond the scope of this study. Until that time, the degradated hydrocarbon fluids will be burned and heat value recovered. Combustion also serves as an acceptable disposal method for degraded products.

VOLUMES OF HEAT TRANSFER FLUIDS PRODUCED, CAPACITY, AND METHODS OF PRODUCTION

Production

Generally, information on the volumes of heat transfer fluids currently being produced in the United States, especially oils (hydrocarbon oils), esters, ethers, and silicone fluids, is considered proprietary and is unavailable. Production data for propylene glycol, ethylene glycol, and fluorocarbons are more accessible and are presented in Table 7. Production of ethylene glycol is much greater than that of the other compounds listed in Table 7, although only a small amount of the volume produced is used in solar applications, as will be apparent from estimates made later in this section. Quantities of fluorocarbons produced are somewhat uncertain because they were calculated from 1976 data, a period during which fluorocarbons were used as aerosol propellants. Industrial personnel stated that production dropped 50% when the propellant market was lost as a result of environmental concern about the adverse impact of fluorocarbons on the atmospheric ozone layer. Production data for Freon TA could not be located.

TABLE 7. PRODUCTION OF ETHYLENE GLYCOL, PROPYLENE GLYCOL, AND FLUOROCARBONS

Heat transfer fluid	Production (10^6 kg/year)	Year	Literature referenced
Ethylene glycol	2090	1979	Chemical and Engineering News (1980)
	1770	1978	Chemical and Engineering News (1980)
Propylene glycol	110*	1979	SRI ** (1979)
Freon 11	80*	1979	SRI (1979), Industrial Contact
Freon 114	18*	1979	SRI (1979), Industrial Contact
Freon TA	Unknown	--	--

*Extrapolated from referenced data.
**Stanford Research Institute.

A limited amount of production data for hydrocarbon oil, ester, ether, and silicone heat transfer fluids was obtained through personal communications with industrial personnel (see Table 8). These data provide a rough production estimate for many of the heat transfer fluids. Combined production figures in Table 8 are much smaller than those of Table 7, indicating a relatively lower demand for these fluid types.

Production Methods and Capacity

Except for ethylene glycol, propylene glycol, and fluorocarbons, manufacturing processes for the production of heat transfer fluids are proprietary. Industrial personnel describe the hydrocarbon oil heat transfer fluids

as having the physical characteristics of common motor oils, but provided little information on their methods of production.

TABLE 8. PRODUCTION ESTIMATES FOR CERTAIN HEAT TRANSFER FLUIDS

Heat transfer fluid	Production (10^6 kg/year)	Year
Therminol 44	1.8	1980
Therminol 55	3.4	1980
Therminol 60	1-1.4	1980
Therminol 66	7-9	1980
Therminol 88	0	1980
Dowtherm A Dowtherm G Therminol VP-1	11	1980

Processes for the production of ethylene glycol, propylene glycol, and fluorocarbons are outlined in numerous publications, including Shreve (1977) and SRI (1979). Ethylene glycol is produced from ethylene feedstock through three major routes:

1) reaction of ethylene with hydrochlorous acid to produce ethylene chlorohydrin followed by hydration to ethylene glycol;

2) oxidation of ethylene followed by hydration of the oxide to form ethylene glycol; and

3) Reaction of ethylene with acetic acid with a catalyst to form mono- and diacetates which are then hydrolyzed to form ethylene glycol.

Propylene glycol is produced from propylene via a propylene oxide intermediary. In general, the most important method of glycol formation is through hydroxylation of the necessary alkene (Morrison and Boyd, 1973). Most fluorocarbons are produced by the liquid phase reaction of a chlorocarbon with pure hydrogen fluoride and an antimony halide catalyst (SRI, 1979).

Capacity data for the production of heat transfer fluids is also limited and in most cases considered proprietary. Available information from the literature and from industrial personnel on production capacities is presented in Table 9. Calculated quantities assume a 5% annual production growth rate from data obtained in 1974 and 1976, respectively. Production data for fluids not listed in Tables 8 and 9 are not available due to the proprietary nature of the fluid.

TABLE 9. CAPACITY FOR PRODUCTION OF HEAT TRANSFER FLUIDS

Heat transfer fluid	Production capacity (10^6 kg/year)	Year
Ethylene glycol	2270	1976
	2760*	1980
Propylene glycol	310	1974
	420*	1980
Dowtherm A, Dowtherm G, Therminol VP-1	11	1980
Therminol 44	7	1980
Therminol 55	7	1980
Therminol 60	14-18	1980
Therminol 66	14-18	1980
Freon 11	160	1974
Freon 114	36	1974

*Calculated

Industrial personnel have stated that, if their projections are correct and solar plants were built, the demand for heat transfer fluids would be greater than current production capacities. However, several other factors will affect the balance between supply and demand. First, once construction of large-scale solar plants is started, the lag time between initial and final construction of the plants themselves will provide ample time for producers of heat transfer fluids to increase their production capacity to meet the demand. In most cases, the basic feedstocks for heat transfer fluids are in plentiful supply. Secondly, the current total demand for heat transfer fluids is in general much lower than production capacity, as can be seen by comparing Tables 7 through 9. On the basis of trends, the supply of heat transfer fluids should meet demands created by the construction of solar plants.

It is informative to estimate the maximum projected use of heat transfer fluids. For example, the total projected IPH energy demands for 1990 are 1×10^{18} joules (1.0 quads) from Table 3. As stated previously, the parabolic trough will be the most widely used focusing mechanism for IPH, as part of either LFDR-TR or LFDR-TC collector systems. Assuming that oil will be the transport media used to obtain sufficiently high IPH temperatures, and using Table 10, the quantities of fluids required under two extremes of plant sizes are:

Plant Size	Total Number of Plants	Quantities of Fluid Required (kg)
1 MW_t	32,000	7.4×10^8
1000 MW_t	32	9.8×10^8

The total quantity of fluid required is thus comparable, regardless of plant size and number of applications. Note that these quantities are one to two orders of magnitude higher than the present-day production capacities estimated for typical heat transfer fluids such as Dowtherm or Therminol, but are a modest fraction of production for more common materials such as the glycols (see Table 9). In either case, the approximately 10-year lead time available for increased production before widespread deployment of the solar systems should allow an orderly increase in production capacity to meet demands. Since there have been no large scale commitments for one particular fluid, however, manufacturers of the materials will not begin increasing production capacity until a demand can be forecast reliably.

SECTION 6

FLUID RELEASE AND ENVIRONMENTAL FATE

RELEASE SCENARIOS

This section discusses the mechanisms through which heat transfer fluids could be released to the environment during each phase in the life cycle of the fluid. Release scenarios are presented for manufacturing, storage, transportation, and operation settings.

Manufacturing, Storage, and Transportation Settings

There are three phases in the life cycle of a heat transfer fluid prior to its use as a working fluid in a solar thermal plant. These include its manufacture, storage, and transport to the plant site. Mechanisms of release to the environment from any of these phases can be expected to be similar to those encountered currently for other fluids, such as petroleum products that experience analogous initial life cycle phases.

Most organic heat transfer fluids and freeze protection additives (e.g., ethylene glycol) that will be used in solar thermal applications will be manufactured at existing production facilities. Most of these facilities are located in the northeastern, northcentral and Gulf Coast states (Parts et al., 1980). This will require that the fluids be transported relatively long distances for use with near-term solar applications located in the Southwest. The most likely modes of transportation will be railcar or truck, depending on the volumes to be shipped and access to the sites.

In some instances, particularly with the molten-nitrate salts, it may be more economical to manufacture the fluid onsite than to buy the prepared mixture from a manufacturer (Tracey, 1978). In this case, the raw materials would be transported to the plant site and the salt mixture would be mixed and melted onsite. The release scenarios in this case would differ somewhat from those of a working fluid that is produced in a manufacturing facility and then shipped to the plant.

Heat transfer materials that are shipped or stored in the solid phase have an advantage over heat transfer fluids. Spills are likely to occur less frequently and are more confined if they do occur. Materials that are stored or shipped as solids include nitrate salts and sodium and potassium metals.

Operational Scenarios

This section describes the operating phase in the life cycle of a heat transfer material used in a solar application. The operating scenario will differ somewhat with each type of heat transfer material and with the solar system concept. Basically, however, the working fluid is circulated through the receiver, where it collects heat from the incident solar radiation. From the receiver, the fluid is pumped either through the heat exchanger that interfaces with the process plant or to a storage facility. During plant downtime, the fluid in the transport system is drained to hold tanks. Central receiver systems recirculate the fluid from the tower base to the receiver at the top of the tower. Distributed receiver systems employ extensive piping networks that route the working fluid from a central facility to individual collector/receiver units.

Proposed solar thermal concepts are highly automated and require little interface with plant operators. Flow is controlled with automatic valves, although manual valves are available as a backup or to allow isolation of particular pipe sections during maintenance operations. Check valves prevent the backflow of fluids in the network piping systems.

With both central and distributed receiver concepts, the diameter of the supply and return piping can vary from a few inches up to several feet depending on the plant size and the operating conditions. Piping for both types of systems will require expansion joints or loops to allow for the expansion and contraction of pipes over the wide range of temperature that the pipes will experience during normal plant operation. Because most of the distributed receiver systems track the sun, flexible piping must be used to accomodate movement. Flexible piping is not required for central receiver systems. Carbon steel pipe is used up to temperatures of about 450°C. Between 450 and 540°C, stainless steel pipe must be used. Beyond 540°C, high temperature alloys, such as Inconel, must be used. All straight runs of pipe are insulated with several inches of calcium silicate and/or fiberglass insulation. Pipe runs are above the ground and are mounted on pipe supports.

Storage tanks are fabricated of the same materials as the piping system as determined by the maximum temperature of the working fluid. Storage systems proposed for all heat transfer fluids, with the exception of air, have been designed with fluid containment dikes to control any spills that may occur.

The use of organic working fluids will require a sidestream reprocessing unit to remove thermal degradation products that can inhibit heat transfer and fluid flow. Furthermore, ullage units must be provided to control the inert nitrogen atmosphere maintained over the storage tanks and to purge the volatile degradation products from the vessels (Ullman, 1979b).

Concepts using molten salts or metals will need steam or electric heat tracing to prevent solidification of material in the pipes when the ambient temperature drops below the freezing point of the material.

The quantity of working fluid required for a particular concept depends on a number of factors. Among these are:

1) the application (electric or non-electric);

2) the heat capacity of the fluid; and

3) the efficiency of the collector/receiver system.

In general, electric applications require larger quantities of heat transfer fluids because the efficiency of converting thermal energy to electrical energy is much less than unity. The greater the heat capacity of the working fluid, the smaller the volume requirement. Lastly, the greater the efficiency of the collector/receiver system, the fewer units needed to supply a given power level. This, in turn, leads to smaller volume requirements.

From PNL's comparative analyses (Apley, 1980; Laity, 1980; Bird, 1981) of solar thermal concepts for power and process heat systems, estimates were made of the quantity of working fluid required for various systems at different temperatures and power levels. Estimates of the quantity of working fluid for a single plant are listed in Table 10 for plant sizes of 1 to 1000 MW(t) for IPH or agricultural applications and from 0.5 to 300 MW(e) for electric plants. It is important to realize that these quantities represent only the volume of the working fluid (that is, the holdup volume in the transport system); if storage is used in conjunction with the solar facility, these numbers would represent only a small fraction of the total volume of heat transfer fluid used in the plant. However, thermal storage will be used sparingly in the future because it is not currently cost-effective. To achieve the mid-term (1990-2000) total market potential for solar thermal plants, large quantities of working fluids would have to be deployed.

Mechanism, Volumes, and Dynamics of Fluid Release

A University of California study (Ullman, 1979b) has identified three types of mechanisms that could lead to the accidental release of working fluid from a solar thermal plant. These mechanisms are: 1) the design limit of a component or material is exceeded; 2) an anomaly occurs; or 3) substandard materials or procedures are used. These mechanisms apply in all phases of the working fluid life-cycle: manufacture, storage, transportation, and operation.

The first mechanism of release occurs when an event exceeds a planned design specification. Examples of this type of event include seismic activity, sabotage, fire, fluid overheating, or corrosion. Although all plants have design levels in each of these areas, it is probable the design level may be exceeded. Designing the system to withstand any level of an event is generally not warranted on the basis of cost or not possible from a technical standpoint.

The second mechanism of release, the occurrence of an anomaly, involves an unforeseen event for which design considerations were not made. Examples of these events include failures of other plant subsystems or abnormal external events, such as an aircraft accident.

TABLE 10. QUANTITY OF HEAT TRANSFER FLUID REQUIRED FOR SOLAR THERMAL CONCEPTS

Concept	Electric			Non-Electric		
	Temp (°C)	Fluid	Quantity* (liters) x 10^4	Temp (°C)	Fluid	Quantity** (liters) x 10^4
PFCR	560	Salt	0.4 to 130	120	Water	0.02 to 8
	815	Air	-----(Brayton)	230-300	Oil	1.00 to 800
				565	Salt	0.26 to 150
PFDR	450	Salt	5.0 to 600	120	Water	0.04 to 26
	815	Air	-----(Brayton)	230-300	Oil	1.50 to 1900
	815	Air	-----(Stirling)	565	Salt	3.80 to 800
FMDF	450	Salt	5.0 to 800	120	Water	0.03 to 19
				230-300	Oil	1.50 to 1900
				565	Salt	3.00 to 760
LFCR	450	Salt	2.0 to 1600	120	Water	0.08 to 38
				230-300	Oil	3.80 to 3000
				565	Salt	1.10 to 1500
LFDR-TR	450	Salt	2.0 to 2000	120	Water	0.03 to 26
				230-300	Oil	2.30 to 3000
				565	Salt	0.76 to 2300
LFDR-TC	300	Oil	4.0 to 300	120	Water	0.03 to 30
				230-300	Oil	2.30 to 3000
LCNT	230	Oil	10.0 to 5900	120	Water	0.11 to 38
				230	Oil	3.80 to 3800

*Range of values for 0.5 MW(e) to 300 MW(e).
**Range of values for 1 MW(t) to 1000 MW(t).

The last type of mechanism occurs when improper or negligent actions are taken during normal or off-normal operation of the plant or when materials used in the construction or the operation phase of the plant do not meet the design specifications.

Since many of the solar plant operations are analogous to refinery operations, spill percentages for heat transfer fluids, particularly oils, are likely to be of the same order of magnitude as those experienced in the oil industry. Spills occur most frequently during bulk transfer of material, such as when tank trucks are loaded from storage (DOT, 1980). Next to bulk transfers, spills occur most frequently during highway transport; however, storage facilities rank second only to bulk transfers in terms of volume. Data on all sources of spills in the oil industry (Petty, 1981) were normalized for those sources pertinent to the life cycle of heat transfer fluids. Normalized projections for the volume of spills likely to occur with solar heat transfer fluids are listed in Table 11.

TABLE 11. NORMALIZED VOLUME OF SPILLS AND SPILL FACTORS FOR SOLAR HEAT TRANSFER FLUIDS

Location	% volume	Spill factor x 10^6
Manufacture	3	0.5
Bulk transfer	65	17.4
Rail transport	3	15.5
Highway transport	11	2.3
Storage	17	3.3

Table 11 also lists spill factors (defined as the ratio of the amount spilled to total amount of material handled in a particular operation) for each of the five categories. It is informative to compare quantities of materials that might be spilled to standard oil industry operations. The use of heat transfer fluids at solar energy facilities is comparable to operations involved in oil refining, thus the spill factor for manufacturing operations will be used. If this factor is assumed to be 1×10^{-6}, and a projection of 9×10^8 kg (see Section 5) is used as the quantity of fluid involved in annual energy production, then approximately 900 kg/year is obtained as the estimated total spillage rate. Release from all other steps in a fluid's life cycle (Table 11) is estimated to be 15,000 kg/year. For comparison, the spillage rate of a single 100,000 barrel per day oil refinery is calculated to be 55,000 kg/year. Thus, the amount of heat transfer fluids that might enter the environment is miniscule compared to normal handling of common industrial materials.

Experience within manufacturing facilities indicates that sources of working fluid leaks during routine operation will mainly be a result of component failure. Components that fail include piping, flanges, welds, valves, expansion and flexible joints, and pressure vessels.

Component failure rate data indicates that flexible joints and gaskets leak most frequently, followed by flanges and elbows, and expansion joints. Information indicates that welds are the least likely of the components to fail. The following table lists mean failure rate data for various transport piping system components in order of decreasing failure rate (Ullman, 1979a).

TABLE 12. COMPONENT FAILURE RATES

Component	Type of failure	Median failure rate ($hours^{-1}$)
Flexible joints	Leak	3×10^{-6}
Gaskets	Leak	3×10^{-6}
Expansion joints	Leak	3×10^{-7}
Flanges and elbows	Leak or rupture	3×10^{-7}
Pressure vessels	Leak or rupture	3×10^{-7}
Pipes	Rupture	3×10^{-8}
Valves	External leak or rupture	1×10^{-8}
Welds	Leak	3×10^{-9}

By analogy, spill rates in heat transfer fluid manufacturing facilities (particularly heat transfer oil facilities) are expected to be on the same order as those encountered in crude oil refineries, as shown in Table 11, where the average spill factor was calculated over a four-year period based on annual refinery spill data in gallons (Coast Guard) and annual average refinery throughput (McAfee, 1980). This value is about an order of magnitude smaller than spill factors for most other methods of oil transport (rail, truck, pipeline, tanker).

Sources of working fluid leaks within an operating solar plant will largely be a result of component failures in the fluid transport and storage systems. Components that may fail include piping, flanges, welds, valves, and expansion and flexible joints.

The probability of releasing working fluids to the environment in an operating solar thermal plant is largely a function of the type of solar thermal concept (for example, central versus distributed), the type of working fluid employed, and to some extent the temperature of the working fluid.

Central receiver systems have a lower probability of releasing working fluids to the environment than do distributed systems, because the central systems do not require the extensive piping networks used with distributed

receiver designs. Also, central receivers do not use the flexible connectors required by systems with moving distributed receivers. As shown in the preceding table, this fitting is more subject to failure than other fittings. Of the distributed concepts, the PFDR (parabolic dish) is more prone to accidental release of working fluid than the parabolic trough system (LFCR-TR, LFCR-TC, LCNT). The straight-line geometry of the parabolic trough concepts provides significant benefits compared to the complex piping arrangement of the parabolic dish system. At a given power level the dish systems have a great deal more piping components and therefore more potential locations for leaks than the trough systems.

Leak rates for three 100 MW(e) systems operating at 0.4 capacity factor are summarized in the following table (Ullman, 1979a), which has been derived from Table 12.

TABLE 13. LEAK RATE IN 100 MW(e) SYSTEMS (LEAKS/YEAR)[a]

Component	Parabolic dish	Parabolic trough	Central receiver
Valves	4	2	0.003
Connectors	300	100	0.3
Welds	0.8	1	0.2
Expansion	30	6	--
Flexible joints	500	200	--
Piping--minor leak	10	2	0.4
--major rupture	0.3	0.07	0.01
Total	800	300	1

a) 1 year = 3500 hours at 0.4 availability.

The study by Ullman (1979b) identifies potential fluid release modes for particular storage systems. Failure of any unit within the storage subsystem can lead directly to fluid release. Some of the mechanisms of release from storage are listed below.

Event	Mechanism	Result
Desuperheater failure	Auto-ignition temperature is exceeded	Explosion or fire
Fluid maintenance unit failure	Auto-ignition temperature is exceeded	Explosion or fire
Ullage maintenance failure	Air ingress Overpressurize	Fire Vent to atmosphere
Condenser failure	Water ingress-flashing	Vent to atmosphere

The choice of heat transfer fluid for a given concept implicitly affects the failure rate. Fluids with poorer heat transfer capabilities require larger quantities of fluid, and therfore more tubing. With more piping components, the chance of a leak occurring increases. Fluids with corrosive properties increase the probability of failure, as do fluids with lower auto-ignition temperatures. The operating temperature of the working fluid can affect the failure rate of the system components if the auto-ignition temperature of the fluid is reached or exceeded, or if the fluid vaporizes thereby overpressurizing the system.

ENVIRONMENTAL MATRICES AFFECTED

Release of heat transfer fluids or related effluents via one of the mechanisms described in the preceding section could potentially affect air, water, or soil quality. In turn, factors that adversely affect the air, water, and land will tend to harm the organisms depending on these resources.

Air, water, and land matrices could be affected at any stage in the life cycle of the heat transfer material. The following table summarizes the matrices that could be affected at each stage. Both the form of the material (solid, liquid, gas) and the environmental setting in which it is released can determine which matrix is affected.

TABLE 14. ENVIRONMENTAL MATRICES AFFECTED AT EACH STAGE IN THE LIFE CYCLE OF A TYPICAL HEAT TRANSFER FLUID

Stage	Air	Water	Soil
Manufacture			
- gaseous effects	X		
- liquid effluents		X	X
- solid wastes		X	X
- product leaks		X	X
Storage			
- leaks or spillage		X	X
Transport			
- spillage		X	X
Operation			
- fluid leaks	X	X	X
Disposal			
- burning of organics	X		
- burial		X	X
- recycle	X	X	X

During heat transfer fluid manufacture, there is opportunity for waste by-products to be released to any of the three sectors. The impact on each sector will depend on the properties of the particular effluent or waste

by-product and on the control mechanisms provided by the manufacturing facility. In addition to the possible release of waste by-products, it is possible that the heat transfer product itself may be inadvertently released via a leak or spill. The most likely impact of fluid leaks and spills will be to the water and soil. It is unlikely that air would be affected at this stage because few of the fluids are volatile at ambient temperatures (Parts et al., 1980).

The storage and transport stages have the potential of affecting soil or water through spills or leaks of heat transfer materials. These materials may be either in the solid or liquid phase. The nature of the impact will depend largely on the quality of the spill or leak, the proximity of ground or surface water, and the phase of the material.

During plant operations, there is potential for affecting any of the matrices. The sector most directly affected during plant operation would be the soil; however, leaks or spills of heat transfer fluids could migrate through the soil and contaminate ground or surface water. Effects of fluid spills occurring at near-term solar thermal plants located primarily in the deserts of the Southwest, will, in general, be confined to the soil matrix since supplies of surface and ground water are sparse. Some plants exist or have been planned in the Southeast and the Gulf states. These areas have higher annual rainfalls than their counterparts in the Southwest and consequently ground and surface water contamination will become more important when considering the impacts associated with heat transfer fluid spills for these sites. The use of fluid containment dikes around storage vessels should help to mitigate the impacts of a spill or leak from this subsystem. Loss of fluid from piping will be minimized through use of automatic shutoff valves and manual valves, which will serve to isolate the leak. There is also the potential for release to the air if the fluid vaporizes during plant operation and over-pressurizes system components, or if the fluid leaks to the steam side of a heat exchanger, it could escape to the air through entrainment with the steam.

Some of the potential disposal options for heat transfer fluids are burning, burial, or recycling (Searcy, 1975). As mentioned earlier in the report, burning will be the dominant disposal technique since the industry is not equipped to recycle spent fluids and because recycling is not cost-effective. Burning offers the additional advantage of heat recovery, since most heat transfer fluids provide a net positive amount of energy when combusted. Thus, it is probable that the organic breakdown products, and the organic products themselves upon decommissioning of the plant, could be used as a low grade fuel. Burning of these organics could result in release of hazardous pollutants to the atmosphere. Associated air pollution control equipment may require controlled disposal of solid or liquid wastes. Some of the heat transfer materials or thermal degradation products may be buried, especially those with low heating value. Depending on the availability of water and the leach rate of the material, both soil and water could be affected. Many of the heat transfer fluids could be recycled for reuse in another facility. In this case, any of the matrices could be affected since reprocessing would have much the same impacts as the original manufacturing process.

TRANSPORT AND FATE OF MATERIALS IN THE ENVIRONMENT

This section is divided into two subsections:

1) Transport mechanisms, driving forces, and barriers to movement;

2) Consequences of enviornmental point source contamination.

Information on transport mechanisms is generally not available and more work is required in this area in order to fully characterize the mechanisms. What information could be identified is discussed below.

Transport Mechanisms, Driving Forces, and Barriers to Movement

It is anticipated that solar plants will be designed for containment of heat transfer fluids (Cole et al., 1979; OTA, 1978; Beall et al., 1974; and Hydroscience, 1979). Similar facilities are covered by regulations that emphasize the need for proper design of plants such that all possible leakage or spills could be contained and cleaned up in a safe manner. Process equipment such as packing glands for valves, pumps, and heat exchangers have known failure rates (Ullman, 1979a) and will eventually leak heat transfer fluids at the facility site. Normally containment curbs and fire suppression equipment will be incorporated into plant designs to minimize environmental and safety risks. These designs should restrict movement of heat transfer fluids into the adjacent soils and groundwaters.

Although precautionary measures designed to prevent spills will be incorporated into plant designs, the possibility for spills still exists. Once these potential spills reach soils, it becomes important to minimize the contaminated soil volume and the movement of the spilled material towards groundwaters.

Movement of solar heat transfer fluids through soils will be restricted by environmental and physical conditions. Since many of the solar plants will be constructed in areas of high insolation, very little moisture will be present in the surface soil layers to promote movement of contaminants through the soil. In regions where rainfall is more plentiful, the potential for spills to reach the groundwater will be increased. Physically the viscosities of most of the heat transfer fluids are relatively high (like motor oil), which will restrict movement of heat transfer fluids through the soil. Some of the heat transfer fluids are highly volatile (for example, freons) and will vaporize once exposed to the atmosphere.

Another variable which can be used to estimate how compounds will be transported, once spilled, is the octanol-water partition coefficient (K_{ow}). These coefficients give the ratio or partitioning of a compound in octanol (organic) and water (aqueous). High K_{ow} indicates that the compound has a greater potential to adsorb on organics and soils than substances with lower K_{ow}. This, in turn, implies that the substance has a greater bioaccumulation potential. Those compounds with low K_{ow} prefer the aqueous phase and are more likely to move through the soil column and into the groundwater.

Leo (1971, 1980) has accumulated a vast collection of partition coefficients for organics in various solvents. Table 17 lists those partition coefficients available for various heat transfer fluids. Often, heat transfer fluids are listed by trade name and their composition is proprietary. In these cases, the partition coefficients for major constituents are listed. The glycols will tend to move towards groundwater as evidenced from their low K_{ow}. Most of the hydrocarbons will sorb onto surface soil layers and remain fixed due to their large K_{ow}. Bioaccumulation may be a problem for some of the lighter hydrocarbons.

TABLE 15. PARTITION COEFFICIENTS (K_{ow}) FOR SELECTED HEAT TRANSFER FLUIDS

Heat transfer fluids	Major constituents	Organic phase	Log K_{ow}	K_{ow}
Ethylene glycol	Ethylene glycol	Octanol/water	-1.93	0.012
Propylene glycol	Propylene glycol	Diethyl ether/water	-2.00	0.010
Freon 11	Freon 11	Octanol/water	2.53	340
Freon 114	Freon 114	Octanol/water	2.82	660
Dowtherm E	o-Dichlorobenzene	Octanol/water	3.38	2,400
Therminol 44	Di-2 ethyl adipate	Octanol/water	-	-
Therminol 55 (Alkylated benzenes)	Methyl benzene	Octanol/water	2.70	500
	Ethyl benzene	Octanol/water	3.15	1,410
	Propyl benzene	Octanol/water	3.66	4,570
	Butyl benzene	Octanol/water	4.26	18,200
Therminol 77 (Polyphenyl ether)	Diphenyl ether	Octanol/water	4.00	10,000

Consequences of Environmental Point Source Contamination

Several geo-systems -- including surface soils, groundwater, and air quality -- could potentially be affected by the construction of solar-thermal plants and associated heat transfer fluid spills. The degree to which these systems are affected will be directly influenced by the number of plants constructed in close proximity. This is because most plants will be built in a limited number of regions where high levels of solar insolation are found. Direct consequences of environmental point source contamination to these geo-systems are discussed in the following paragraphs.

The system most likely to be affected by release of solar heat transfer fluids is surface soils. Because of the relatively low amount of moisture falling in these desert regions (Hunt, 1974), few of the spilled materials will be washed into surface or groundwaters. In addition, transport parameters such as octanol/water partition coefficients (K_{ow}) indicate that a majority of the hydrocarbons and silicone-based heat transfer fluid materials (hydrocarbon and silicone) prefer the organic phase and consequently will sorb onto surface soils. The high viscosity of hydrocarbon and silicone oils will also restrict their movement. In general, the volume of heat transfer fluids (oils only) likely to be spilled is small, and the contaminated soil could be removed and cleaned. The solvents listed in Table A-3 of Appendix A could be used for this purpose, or possibly the oils could be incinerated. In a worst case scenario, the soils could be removed to a hazardous waste dump site.

Those heat transfer fluids which, provided the spill is large enough, will tend to move from the surface soils into subsurface soils and the groundwater include ethylene and propylene glycols and water. Due to the desert environment in which many of these solar-thermal plants will be constructed, groundwaters will be lesser in extent and much deeper than in other geographic areas. This will help minimize groundwater contamination. Since the biodegradability of many of these fluids is quite good, the long-term effects of spills should be negligible, except for very large spills. Corrosion inhibitors in aqueous heat transfer fluid systems could contaminate the environment in which they are spilled. However, because they are present in only trace amounts, they should not present any severe environmental problems. In a worst case, collection wells could be constructed and the materials removed to a proper waste disposal site.

With the exception of fluorocarbons, most of the heat transfer fluids are not volatile and should not adversely affect air quality. If freons are spilled in large amounts and in a confined area, air quality will be degraded. However, proper ventilation should minimize this problem due to the high volatility of freons. In addition, both the number of systems using freons as heat transfer fluids and the quantity required for a given application is small. These factors further minimize the likelihood of air quality problems due to freon spills.

SECTION 7

APPLICABLE ENVIRONMENTAL REGULATIONS AND POLLUTION CONTROL TECHNIQUES

IMPACT OF RCRA, TSCA, AND CWA ON THE USE OF SOLAR HEAT TRANSFER FLUIDS

Three acts -- the Resource Conservation and Recovery Act (RCRA), the Toxic Substances Control Act (TSCA), and the Clean Water Act (CWA) -- could potentially impact decisions made on which heat transfer fluids will be used by the solar industry. RCRA, however, will probably have more impact on these decisions than the other two acts simply because it concerns the hazardous nature of chemicals used in commercial applications more so than the other two acts. TSCA is aimed at reviewing new chemical products, from a toxicity standpoint, before they enter the marketplace. In most cases the fluids discussed in this study are already available commercially and so TSCA should have negligible impact on existing heat transfer fluids.* The CWA is mainly concerned with the release of effluents, from industrial point sources, into waterbodies. Since solar plants should not generally discharge heat transfer fluids to waterbodies, the CWA will probably have minimal impact on solar energy facilities.

RCRA, on the other hand, deals explicitly with the transportation, storage, and disposal of materials which are classified as hazardous. In order to determine if a material is hazardous, RCRA (May 19, 1980 Federal Register) lists both compounds and criteria which may be used to determine if a specific waste is hazardous. Using these criteria, the following conclusions can be reached regarding the classification of solar heat transfer fluids reviewed in this study:

1) None of the heat transfer fluids identified in this report are explicitly listed in RCRA under specific or non-specific sources.

2) None of the heat transfer fluids identified in this report are explicitly listed in RCRA as hazardous substances.

3) Except for Dowtherm J (flash point of 57°C, closed-cup), none of the heat transfer fluids reviewed can be classified as hazardous because of ignitability limits. Ignitability hazard is defined by a substance that has a closed-cup flash point of less than 60°C, is an oxidizer or an ignitable compressed gas, or is a solid which can ignite at standard conditions.

*Manufacturers of new heat transfer fluids which contain compounds that are not found on the TSCA inventory of chemicals must submit a Premanufacturing Notification to EPA, as described in 40CFR720.13.

4) None of the fluids would be expected to be classified as hazardous from a corrosivity standpoint, with the possible exception of the salts such as HITEC.

5) Except for a few of the high temperature heat transfer fluids (for example, sodium, HITEC), none of the fluids would be expected to be classified as hazardous from a reactivity standpoint.

One of the questions which cannot be answered at this time is whether the heat transfer fluids could be classified hazardous based on the proposed extraction procedure (EP) test. Results of EP tests for these fluids are not available at this time.

CONTROL AND CLEANUP RESPONSES

As discussed earlier, the mechanisms likely to result in the greatest volume and frequency of releases into the environment involve storage and transfer operations. For these operations, control consists of adequately engineered containers or vessels, and appropriate procedures for handling the materials. Except for the inorganic salts or metal fluids, no special handling methods or container systems are likely to be required beyond the usual industry practices in dealing with petroleum products or industrial chemicals. Any application involving use of eutectic salt mixtures must consider corrosion problems and must prevent human contact with chemicals. Such procedures will be part of the system design and operation requirements. Similar problems exist if liquid metals were to be used as heat transfer agents. Control methods are likely to consist of over-designed components and a design that minimizes human presence around the transfer subsystem.

It will be necessary to institute measures for containment of materials where spills or leaks are likely to occur. The present industry standard in this regard consists of sumps or physical barriers constructed around storage and loading areas to prevent spreading of the fluids and to facilitate clean-up. The plant site itself should also be outfitted with similar control systems. Such control measures are impractical for transportation-related incidents, but often are constructed at the site of an accident as part of the cleanup operation.

Since projected failure reates are quite low for hardware components within the heat transfer subsystems of solar facilities, no control measures other than containment are envisioned. Typically the fluids are nonvolatile and are considered to be relatively non-toxic. Therefore, precautions with regard to releases into the atmosphere will probably not be taken.

Control and cleanup of spilled heat transfer fluids will usually involve small, isolated spills. The greatest initial danger from the spill of heat transfer fluids will be fire because many of the heat transfer fluids are flammable. Parts el al., (1980) obtained a list of fire extinguishing agents for many of the fluids from the product manufacturers. These agents are presented in Table A-1 in Appendix A. Many of the extinguishing agents suggested in Table A-1 are also used to extinguish conventional hydrocarbon fires.

Once a potential heat transfer fluid spill is contained and the danger of fire minimized, cleanup will begin. Parts et al., summarized manufacturers' responses to questionnaires that asked them to provide information on how to cleanup their respective heat transfer fluid(s) (see Table A-2). In most cases, simple dilution with water, or detergent and water, will cleanup spilled heat transfer fluids. However, in some cases, once heat transfer fluids are spilled, it will be necessary to use solvents to remove spilled fluids from process equipment and instrumentation. Parts (Table A-3) reviews those solvents considered appropriate for a variety of heat transfer fluids.

After heat transfer fluid spills are contained and cleaned up, the waste materials (solvents, heat transfer fluid, etc.) must be disposed of or recycled. Only when the solar industry becomes large will it be economically attractive to recycle spent heat transfer fluids (Searcy, Ed., 1978). For these same economic reasons, recycle of degradation products is unfeasible at this time.

In general, spent or spilled heat transfer fluids can be recycled, landfilled, burned, or sewered, depending on the toxicity of particular fluid. Searcy (Ed., 1978) identifies disposal practices currently used for glycols, silicones, hydrocarbons, and freons. His findings are summarized in the following paragraphs.

Both ethylene and propylene glycols are more biodegradable than any of the other heat transfer fluids, and are commonly discharged into sewage systems. The effects of glycols on sewage systems are not well understood; however, diluting glycol solutions by a factor of five before discharging is generally considered adequate. Large-scale releases may not be acceptable, especially in the presence of chlorine (at sewage treatment plants) where chlorine-glycol compounds could be formed that are considerably more toxic than glycols alone. Biological pretreatment may be necessary before large-scale release of glycols to sewage treatment plants can occur. Incineration is recommended for propylene glycol, according to one manufacturer (OHM-TADS).

Hydrocarbon oils, although currently not commonly used, will be disposed of as are most waste oils. Disposal methods will include recycling, incineration, land farming, and possibly dust control. Recycle of a spilled heat transfer hydrocarbon oil will be very similar to that of conventional waste oil recycling processes, and will probably use existing facilities. Currently, waste oils are commonly disposed of by combustion, resulting in a net recovery of energy. Care must be taken so that the combustion occurs cleanly enough that air quality is not significantly deteriorated. Those hydrocarbon heat transfer oils with low toxicity may be usable on unpaved roads for dust control. Synthetic hydorcarbon fluid disposal techniques are limited and probably will depend on how closely these compounds resemble conventional hydrocarbon oils. In some cases synthetic hydrocarbon oils may be diluted with conventional hydrocarbon oils to make them more amenable to existing waste oil reprocessors where they can be recycled, incinerated, or possibly land farmed.

Silicone-based fluids are projected to become much more popular for use as heat transfer fluids. However, their current rate of usage does not make it economically attractive to recycle these fluids. Silicone oil wastes are currently disposed of through carefully controlled incineration, but the cost may make this prohibitive for individual solar plants. Special collection services will be necessary in conjunction with centralized incinerators for this technique to be viable. Landfill may be an acceptable disposal technique, although no long-term environmental studies have been completed that address this method. More information is required in order to justify landfill disposal of silicone-based oils.

Freon heat transfer fluids are quite volatile and unless contained will escape to the atmosphere very quickly. Although venting is a commonly used disposal method, concern over the effects of freons on the atmospheric ozone layer may prevent its usage. If large volumes of freon are spilled, it may be possible to collect and recycle the liquid for reuse.

SECTION 8

REVIEW OF FEDERAL R&D ACTIVITIES ASSOCIATED WITH MANUFACTURE AND DISPOSAL OF HEAT TRANSFER FLUIDS

Federal R&D activities investigated include those under the auspices of the United States Department of Energy (DOE), the United States Environmental Protection Agency (EPA), and the Electric Power Research Institute (EPRI). EPRI, although not a Federal organization, reflects national concerns with respect to the power industry in its research activities.

In summary, very little research effort (in terms of dollars) is being spent on the manufacture and disposal of heat transfer fluids, and over the next five years very little funding is planned for these types of programs (DOE, 1980; EPA, 1980; EPRI, 1980). To date most of the data pertaining to manufacture and disposal of heat transfer fluids has been provided by the fluid manufacturers themselves (Parts et al., 1980). The following sections provide details from which these conclusions were derived.

The DOE solar energy program is divided into eight subcategories which include:

- Biomass Energy Systems
- Photovoltaic Energy Systems
- Wind Energy Conversion Systems
- Solar Thermal Power Systems
- Ocean Systems
- Agriculture and Industrial Process Heat
- Active Solar Heating and Cooling
- Passive and Hybrid Solar Heating and Cooling

Total initial program funding for fiscal year 1981 was $652 million, up from $596 million in fiscal year 1980. Photovoltaic and solar thermal energy systems received the greatest emphasis within these budgets; each accounted for about 20% of the total funding.

Specific programs with DOE funding greater than $100K are reviewed in a publication by DOE (1980). Programs that pertain to the manufacture and storage of heat transfer fluids are listed in Table 16. None of the programs focus exactly on the area of interest, but may dedicate some funding to these areas. Even if each of the projects' funds were totally used to investigate the manufacture and disposal of heat transfer fluids, less than one-half of 1% of the DOE solar budget would be dedicated to this task. Since none of the five projects listed in Table 16 is totally dedicated to this research effort, the actual percentage is much lower.

EPRI, in their five-year overview and strategy document (EPRI, 1980), does not indicate any plans to study heat transfer fluids. Their major studies in the solar area include solar-thermal conversion, photovoltaics, wind, and technical assessments. Their studies in the pertinent solar-thermal area will use air (Brayton cycle) as a heat transfer fluid. Unless this emphasis (using air as a heat transfer fluid) changes to using fluids other than air, little research funding in this area can be expected from EPRI in the near term.

TABLE 16. DOE PROGRAMS RELATED TO THE MANUFACTURE AND STORAGE OF HEAT TRANSFER FLUIDS

Contractor/location	Funding	Purpose of study
Babcock and Wilcox (Barberton, OH)	$541,944	Conceptually design an advanced water/steam receiver.
Honeywell, Inc. (Minneapolis, MN)	$171,033	Will collect a quantitative set of experimental data to evaluate a particular design concept for storage of thermal energy vs heat of fusion in salts.
Martin Marietta (Denver, CO)	$216,500	Provide data on techniques for low cost containment of molten salt storage media.
Oak Ridge National Laboratory (Oak Ridge, TN)	$245,000	The overall objective of this project is to provide the DOE/OTEC program with assistance in the planning, execution, and analysis of the heat exchanger development program, to perform ad hoc and limited subcontractor work in specialized research areas, and to conduct heat transfer experiments critical to the early realization of advanced and cost-effective heat exchangers for OTEC.
SERI (Golden, CO)	$760,000	Develop receivers for high temperature (600°K) solar applications.

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APPENDIX A

MANUFACTURERS' RECOMMENDED AGENTS FOR CONTROL OF HEAT TRANSFER FLUID ACCIDENTS*

This appendix tabulates information obtained from manufacturers by Parts (1980) on control and cleanup of released heat transfer fluids. Table A-1 lists the manufacturers' recommendations for fire extinguishing agents to be used when fluid combustion accompanies release. Table A-2 lists clean-up methods which manufacturers recommend for leaks or spills of various heat transfer fluids. Finally, Table A-3 lists solvents for heat transfer fluids.

*These lists are provided as background information; listing of various agents or methods does not constitute endorsement or recommendation for use by the U. S. EPA.

APPENDIX A

TABLE A-1. MANUFACTURERS' RECOMMEND FIRE EXTINGUISHING AGENTS FOR HEAT TRANSFER FLUIDS[a]

Fluid	Agents
Hydrocarbons	
Petroleum-based aliphatic hydrocarbons	
Caloria HT-43	CO_2, dry chemical, foam, water spray, or fog.
Mobiltherm 603	CO_2, dry chemical, or foam.
Silogram heat transfer fluid 43	Same fire extinguishing agents that are applied to oil fires.
Synthetic aliphatic hydrocarbons	
Brayco 888	CO_2 or dry chemical.
Brayco 888 HF	CO_2 or dry chemical.
H-30	CO_2 or foam.
Uniroyal PAO-13C	CO_2, dry chemical, foam, or water.
Aromatic hydrocarbons	
Dowtherm J	Dry chemical, steam, water spray, or mist.
Dowtherm LF	Dry chemical, steam, water spray, or mist.
DXE	CO_2, dry chemical, foam or water spray. Water spray may be used to flush spills away from exposure.
Mobiltherm 600	CO_2, dry chemical, or foam. Fire-fighters must use self-contained breathing apparatus.

Continued

TABLE A-1. (Continued)

Fluid	Agents
MCS-1958	CO_2, dry chemical, foam, water spray, or mist.
MCS-1980	Co_2 or dry chemical.
MCS-2046	CO_2, dry chemical, foam, water spray, or mist.
Therminol 55	CO_2, dry chemical, foam, water spray, or mist.
Therminol 60	CO_2, dry chemical, foam, water spray, or mist.
Therminol 66	CO_2, dry chemical, foam, water spray, or mist.
Therminol 88	CO_2 or dry chemical.
Glycols	
Ethylene glycol-based fluids	
Dowtherm SR-1	CO_2, dry chemical, foam or water mist for neat fluid, none needed for diluted fluid.
Prestone II	CO_2 or dry chemical for small fires; foam for large fires.
UCAR TF-17	CO_2 or dry chemical for small fires, foam and water for large fires.
Zerex	CO_2, dry chemical, or water.
Propylene glycol-based fluids	
Dowfrost	CO_2, dry chemical, foam, or water mist for neat fluid, none needed for diluted material.
UCAR FF-35	CO_2, or dry chemical for small fires, foam and water for large fires.

Continued

TABLE A -1. (Continued)

Fluid	Agents
Esters	
Therminol 44	CO_2, dry chemical or foam.
Ethers	
Dowtherm A	Dry chemical, steam, water spray, or mist.
Dowtherm G	Dry chemical, steam, water spray, or mist.
Silicones	
SF-96 (20)	Any common fire fighting agent.
Syltherm 444	CO_2 or dry chemical.
X2-1162	CO_2 or dry chemical.

[a]Listed agents are those recommended by fluid manufacturers, according to Parts (1980); listing of these agents does not constitute endorsement or recommendation for use by the U.S. EPA.

TABLE A-2. MANUFACTURERS' RECOMMENDED CLEANING METHODS FOR HEAT TRANSFER FLUID SPILLS[a]

Fluid	Cleaning Methods
Hydrocarbons	
Petroleum-based aliphatic hydrocarbons	
Caloria HT-43	Recover free liquids. Pour adsorbent onto spill area. Keep out of streams and waterways.
Mobiltherm 603	Adsorb on diatomaceous earth, sawdust, or sand.
Silogram heat transfer fluid 43	Same methods that are used for the cleaning of oil spills.
Synthetic aliphatic hydrocarbons	
Brayco 888	Wipe up if possible. For larger spills, adsorb on inert adsorbent.
Brayco 888 HF	Wipe up if possible. For larger spills, adsorb on inert adsorbent.
ESH-4	Detergent and water.
ESH-5	Detergent and water.
ESH-6	Detergent and water.
H-30	Powdered oil adsorbers.
Uniroyal PAO-13C	Same as for mineral oil.
Aromatic hydrocarbons	
Dowtherm J	Use an approved solid adsorbent.
Dowtherm LF	Use an approved solid adsorbent.
DXE	Collect or use a solid adsorbent. Incinerate under controlled conditions.
Mobiltherm 600	Adsorb on diatomaceous earth, sawdust, or sand; collect and remove to a chemical disposal area. Protective equipment must be worn if contact is probable.

Continued

TABLE A -2. (Continued)

Fluid	Cleaning Methods
MCS-1958	Flush with water.
MCS-1980	Flush with water.
MCS-2046	Flush with water.
Therminol 55	Flush with water.
Therminol 60	Flush with water.
Therminol 66	Flush with water.
Therminol 88	Flush with water.
Glycols	
Ethylene glycol-based fluids	
Dowtherm SR-1	Flush with water or use an adsorbent.
Prestone II	Dilute and wash with water.
UCAR TF-17	Small spills should be flushed with large quantities of water. Large spills should be collected for disposal.
Zerex	Flush with water.
Propylene glycol-based fluids	
Dowfrost	Flush with water or use an adsorbent.
UCAR FF-35	Small spills can be washed with water. Large spills should be collected for disposal.
Esters	
Therminol 44	Flush with water.
Ethers	
Dowtherm A	Use an approved solid adsorbent.
Dowtherm G	Use an approved solid adsorbent.

Continued

Fluid	Cleaning Methods
Silicones	
SF-96 (20)	Adsorb on Fuller's Earth, sawdust, or other adsorbent. Subsequently, clean the spill area with rags soaked with kerosene or other OSHA-approved solvent. When solvents are used, proper safety precautions must be applied.
Syltherm 444	Adsorb as much as possible with a commercial adsorbent, sawdust, or rags. Use a solvent or detergent-water solution to remove surface film.
S2-1162	Adsorb the liquid with a commercial adsorbent, sawdust, or rags.
Fluorocarbons	
Freon 11	Allow to evaporate in absence of personnel. Ventilate the area.
Freon 114	Allow to evaporate in absence of personnel. Ventilate the area.
Freon TA	Allow small spills to evaporate in absence of personnel and subsequently ventilate the area. Large spills can be removed by adsorbing onto a commercial oil and grease adsorber, transferring the contaminated adsorber into drums, and disposing of the latter. Personnel involved in the cleaning operation should wear self-contained breathing apparatus.

[a]Listed cleaning methods are those recommended by fluid manufacturers, according to Parts (1980). Listing of these methods does not constitute approval or recommendation for use by the U.S. EPA.

TABLE A-3. SOLVENTS FOR HEAT TRANSFER FLUIDS[a]

Fluids	Solvents
Hydrocarbons	
Petroleum-based aliphatic hydrocarbons	
Caloria HT-43	All petroleum solvents.
Mobiltherm 603	Other mineral oils and most organic solvents.
Silogram heat transfer fluid 43	Petroleum solvents.
Synthetic aliphatic hydrocarbons	
Brayco 888	Soluble in usual hydrocarbon solvents. To a lesser extent soluble in chlorinated and oxygenated solvents.
Brayco 888 HF	Soluble in usual hydrocarbon solvents. To a lesser extent soluble in chlorinated and oxygenated solvents.
ESH-4	Hydrocarbons, esters, and ethers.
ESH-5	Hydrocarbons, esters, and ethers.
ESH-6	Hydrocarbons, esters, and ethers.
H-30	Chlorinated solvents, petroleum distillates, benzene, toluene, and xylene.
Uniroyal PAO-13C	Aliphatic and aromatic hydrocarbons, and chlorinated solvents.
Aromatic hydrocarbons	
Dowtherm J	Most hydrocarbons and chlorinated xylenes.
Dowtherm LF	Most hydrocarbons and chlorinated xylenes.
Mobiltherm 600	Mineral oil and most organic solvents.
MCS-1958	Most organic solvents.
MCS-1980	Most organic solvents.

Continued

TABLE A-3. (Continued)

Fluids	Solvents
MCS-2046	Most organic solvents.
Therminol 55	Most organic solvents.
Therminol 60	Most organic solvents.
Therminol 66	Most organic solvents.
Therminol 88	Most organic solvents.
Glycols	
Ethylene glycol-based fluids	
Dowtherm SR-1	Water
Prestone II	Water
UCAR TF-17	Water, acetone, diethanolamine, methanol, monoethanolamine, phenol, and pine oil.
Prophylene glycol-based fluids	
Dowfrost	Water
UCAR FF-35	Water, acetone, diethanolamine, heptane, methanol, monoethanolamine, phenol, and pine oil.
Esters	
Therminol 44	Most organic solvents.
Ethers	
Dowtherm A	Most hydrocarbons and chlorinated xylenes.
Dowtherm G	Most hydrocarbons and chlorinated xylenes.

Continued

TABLE A-3. (Continued)

Fluids	Solvents
Silicones	
SF-96 (20)	Aliphatic hydrocarbons (e.g., hexane, heptane, naphtha), aromatic hydrocarbons (e.g., toluene, xylene), chlorinated hydrocarbons (e.g., carbon tetrachloride, perchloroethylene, trichloroethylene), ethers (e.g., ethyl ether, isopropyl ether), higher alcohols (2-ethylhexanol, lauryl alcohol), and higher ketones (methylethyl ketone, methylisobutyl ketone).
Syltherm 444	Cyclohexane, kerosene, methylene chloride, methylethyl ketone, naphtha, perchloroethylene, toluene, trichloroethylene, turpentine, and xylene.
X2-1162	Kerosene, naphtha, perchloroethylene, toluene, trichloroethylene, and xylene.
Fluorocarbons	
Freon 11	Acetone, dry ethanol, gasoline, dry methanol, and methylene chloride.
Freon 114	Acetone, dry ethanol, gasoline, dry methanol, and methylene chloride.
Freon TA	Acetone, gasoline, methanol, methylene chloride, and silicone oil.

[a]Based on information from fluid manufacturers, according to Parts (1980).